LHC Design Luminosity (round beams)

$$L = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} = \frac{N_1 N_2 f n_b}{4\pi\beta^*\varepsilon}$$

Without crossing angle and hourglass effect

$$\mathcal{L} = 1.2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

With crossing angle

$$\mathcal{L} = 0.973 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

With crossing angle and hourglass effect

$$\mathcal{L} = 0.969 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Integrated luminosity

$$L_{\mathrm{int}} = \int L dt$$

Number of events: N_{ev} = σ(cross section) × L_{int}

units of cross section: 1 barn = 10^{-24} cm^2

units of L_{int}: 1 fb^{-1} = 10^{39} cm^{-2}

Case of symmetric beams

What should be counted for N_1N_2 ?

Luminosity: the basics

$$\boxed{\mathcal{L}} = \boxed{\frac{\mu n_b f_r}{\sigma_{inel}}} = \frac{\boxed{\mu^{meas}} n_b f_r}{\boxed{\varepsilon \sigma_{inel}}} = \frac{\boxed{\mu^{meas}} n_b f_r}{\boxed{\sigma_{vis}}}$$

μ = number of inelastic pp collisions per bunch crossing

n_b = number of bunch **pairs** colliding in ATLAS & CMS (1…2808)

f_r = LHC revolution frequency (11245.5 Hz)

σ_{inel} = total inelastic pp cross-section (Pythia 6: 71.5 mb)

μ^{meas} = number of detected events per bunch crossing

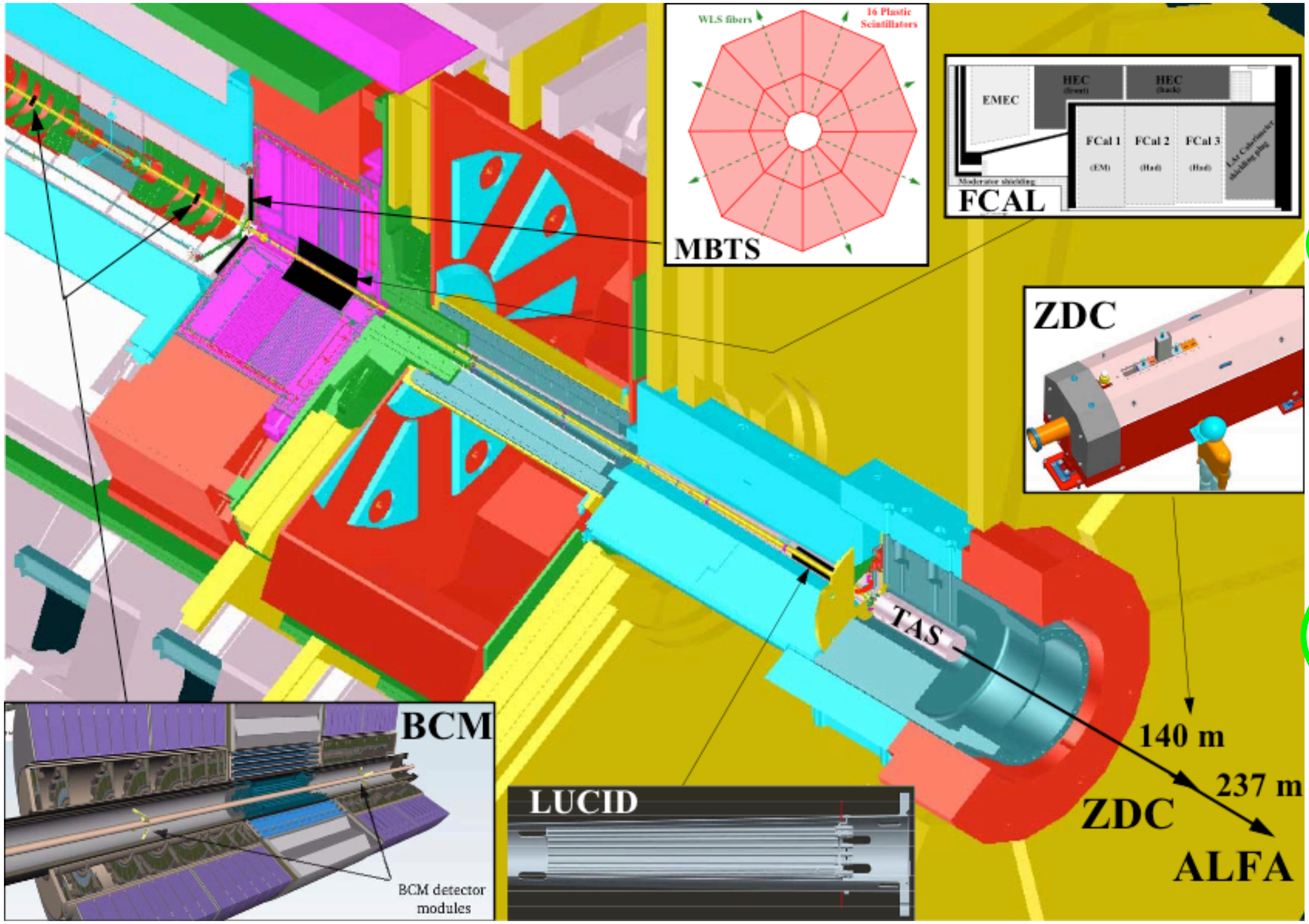
ε = acceptance x efficiency of luminosity detector

σ_{vis} = visible cross-section = luminosity calibration constant

http://witold.web.cern.ch/witold/TEMP/LHC_transit/Luminosity%20material.zip

P. Grafstrom and W. Kozanecki.Prog.Part.Nucl.Phys. 81 (2015) 97-148

Luminosity measurements in ATLAS: online



- **BCM**
  - Event OR/AND
- **MBTS**
  - Event OR/AND
- **FCAL (fwd LAr)**
  - gap currents
- **LUCID**
  - Event OR/AND
  - Hit OR/AND
- **ZDC**
  - event OR A, C
  - event AND

+ALPHA (under construction)

Several $\mathcal{L}$ detectors, for redundancy/consistency (all autonomous)

What the luminosity detectors provide 'naturally' as $\mathcal{L}_{raw}$

- BCM, LUCID, MBTS
  - # of zeroes, of hits, of coincidences, … (several algorithms per L-det)
    - ultimately gives μ_{meas} = measured # of 'events' per unit time (s or BX)
- FCAL
  - total current on A & C sides ~ $\mathcal{L}$ (+ dark current + BIB?)
  - if/when equipped with LUMAT: μ_{meas} ~ LUCID
- ZDC
  - counting rates: A, C (+ A.and.C, A.or.C ?)
- HLT
  - μ_{meas} = measured # of 'events' per unit time (s or BX)
    - from # of reconstructed jet vertices

For a given $\mathcal{L}_{inst}$, $\mathcal{L}_{raw}$ depends on

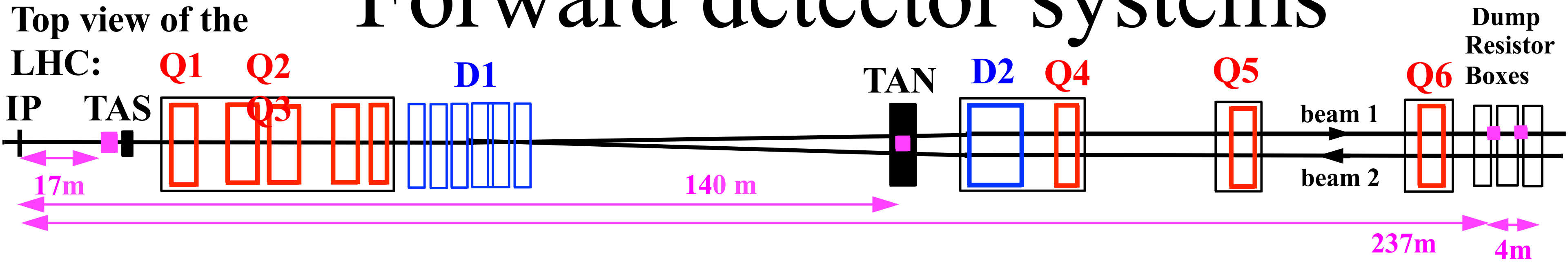
- η distribution (+ particle content)
- subdetector response
- pp cross-section

From $\mathcal{L}_{raw}$ to $\mathcal{L}_{calibrated}$ (conceptually)

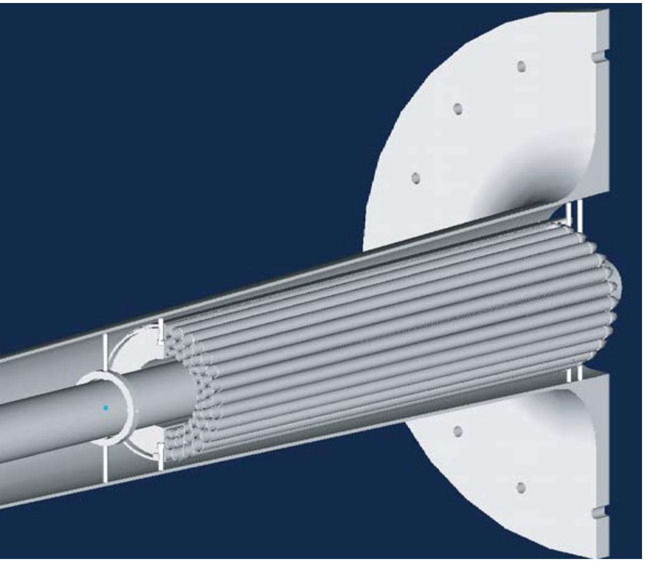
- ❍ 2 steps
  - ⓪ raw data (# hits or 0's) → μ_{meas}
    - dominated by detector response
      - ● some dependence on assumed η/multiplicity distribution
    - µ-dependent (large non-linearities)
    - determined from MC - esssentially
      - ● cannot be obtained from beam-separation scan (but may bias them!)
      - ● later refined by comparing data from different $\mathcal{L}$-dets
      - ● non-linearity can be cross-checked using measured $\mathcal{L}$-decay during long fill
  - ⓪ Absolute scale: $\mu_{meas} \rightarrow \mathcal{L}_{calibrated}$
    - before beam: from MC
    - from beam-calibration scans (2009-10)⟩ ultimately (> 2011) from ALFA
- ❍ on-line quantities relevant to this discussion:
  - ⓪ rawInstLum: (largely) arbitry units, non-linear
  - ⓪ nbrEvtsPerBX (= μ_{meas}) : clear physical interpretation
  - ⓪ instLum (= $\mathcal{L}_{calibrated}$): what we really want

Forward detector systems

Top view of the LHC:



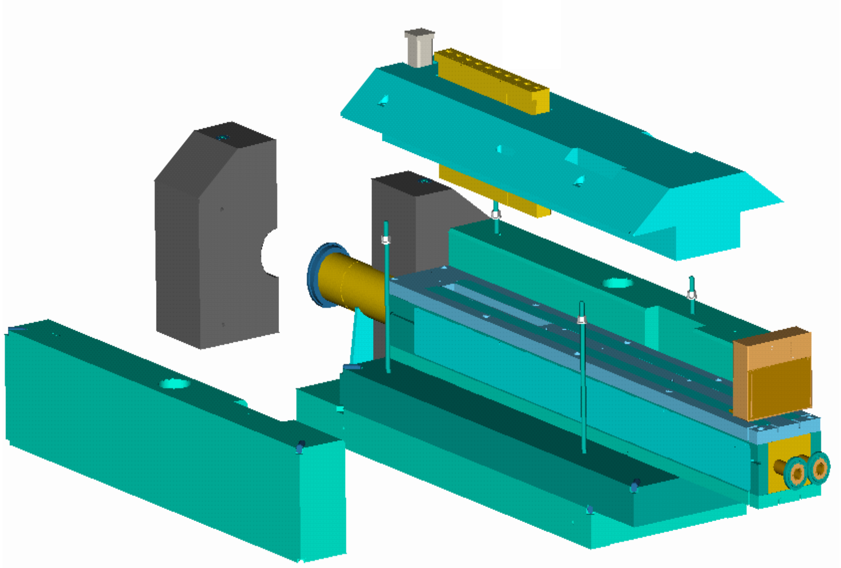
LUCID



Cherenkov tubes

Relative luminosity monitoring.

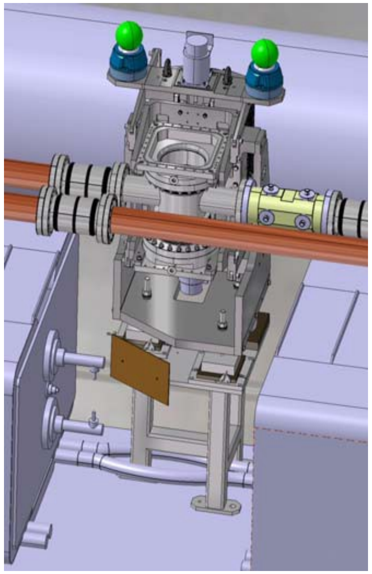
ZD



Tungsten/Quartz calorimeter

Forward physics in both pp and heavy ion collisions.

ALFA



Scintillating fibres in Roman Pots

Absolute luminosity in dedicated LHC runs with special optics and low luminosity

Conservation of probability in quantum mechanics leads to the so called Optical Theorem relating the total cross section to the imaginary part of the elastic scattering amplitude.

$$\sigma_{tot} = \operatorname{Im} f_{el}(t=0)$$

The differential cross section

$$\frac{d\sigma_{el}}{dt} = \pi \, | f_{el}(\theta) |^2$$

with

$$f_{el}(\theta) = \operatorname{Re}[f_{el}(\theta)] + i \operatorname{Im}[f_{el}(\theta)]$$

and the ratio of real to imaginary part of the amplitude denoted as ρ

$$\rho = \operatorname{Re}[f_{el}(\theta=0)] / \operatorname{Im}[f_{el}(\theta=0)]$$

and the total cross section

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \left(\frac{d\sigma_{el}}{dt}\right)_{t=0}$$

The luminosity is related to the interaction rate R via

$$\sigma_{tot} = R_{tot} / L$$

and

$$d\sigma_{el}/dt = (1/L) \; dR_{el}/dt$$

$$L = \frac{1+\rho^2}{16\pi} \frac{R_{tot}^2}{(dR_{el}/dt)_{t=0}}$$

ρ is small (vanishes at t=0) so measurements of elastic and inelastic collision rates can be used to extract luminosity

pp Elastic scattering

$$\left.\frac{dN}{dt}\right|_{t|0} \quad LS\left|f_C + f_N\right|^2 \mid LS\left| - \frac{2a_{EM}}{|t|} + \frac{\breve{u}_{tot}}{4S}\left(i+\check{o}\right){}^{b|t|/2}\right|^2$$

e^-

Ratio of real to imaginary part of the elastic scattering amplitude

Coulomb + Nuclear interaction amplitude

Luminosity

Total cross section

Slope parameter

Coulomb scattering

Coulomb-Nuclear Interference Region

A fit to the measured data in this region will give L, V_{tot}, U and b

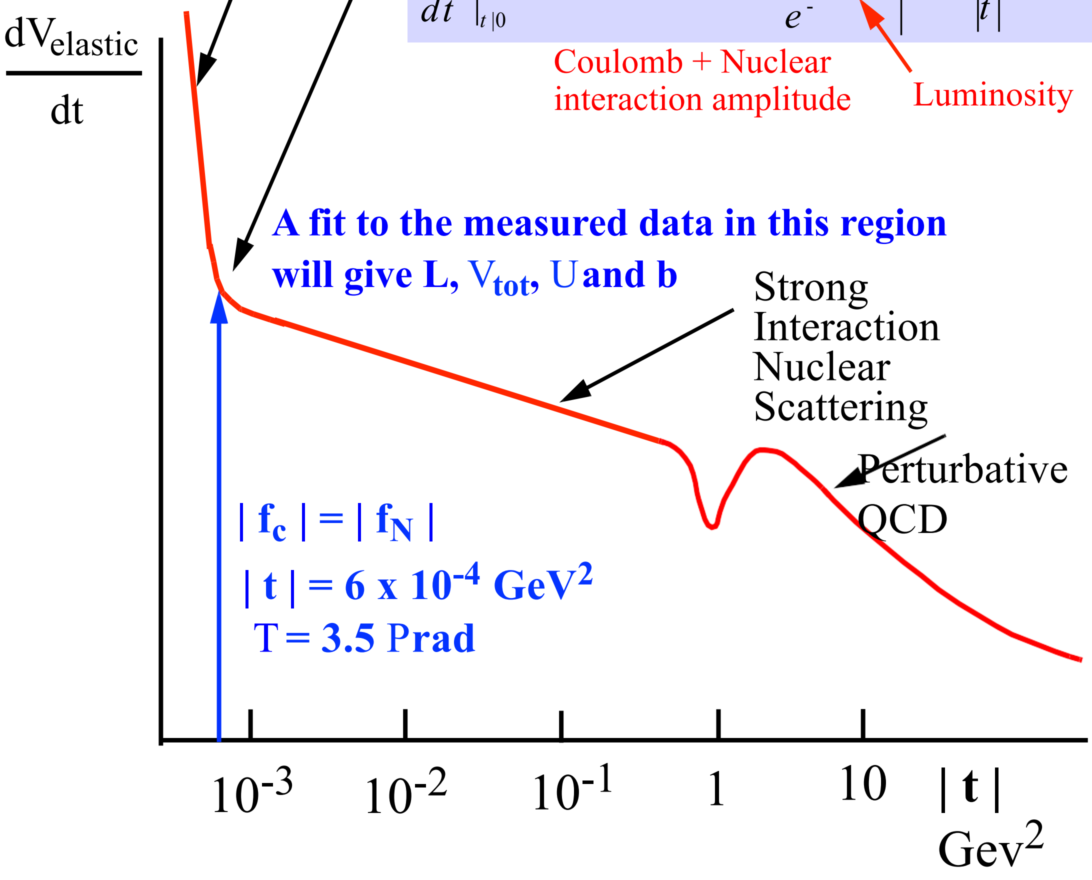
Strong Interaction Nuclear Scattering

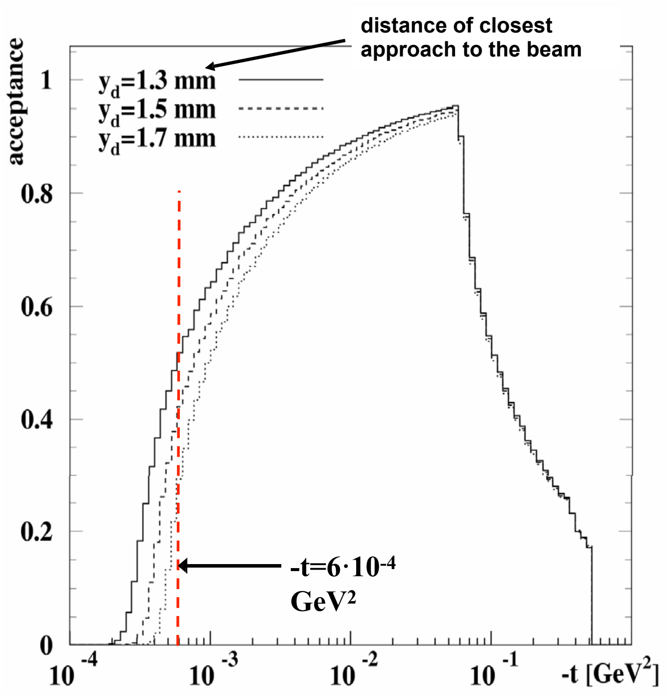
Perturbative QCD

| f_c | = | f_N |

| t | = 6 x 10^{-4} GeV^2

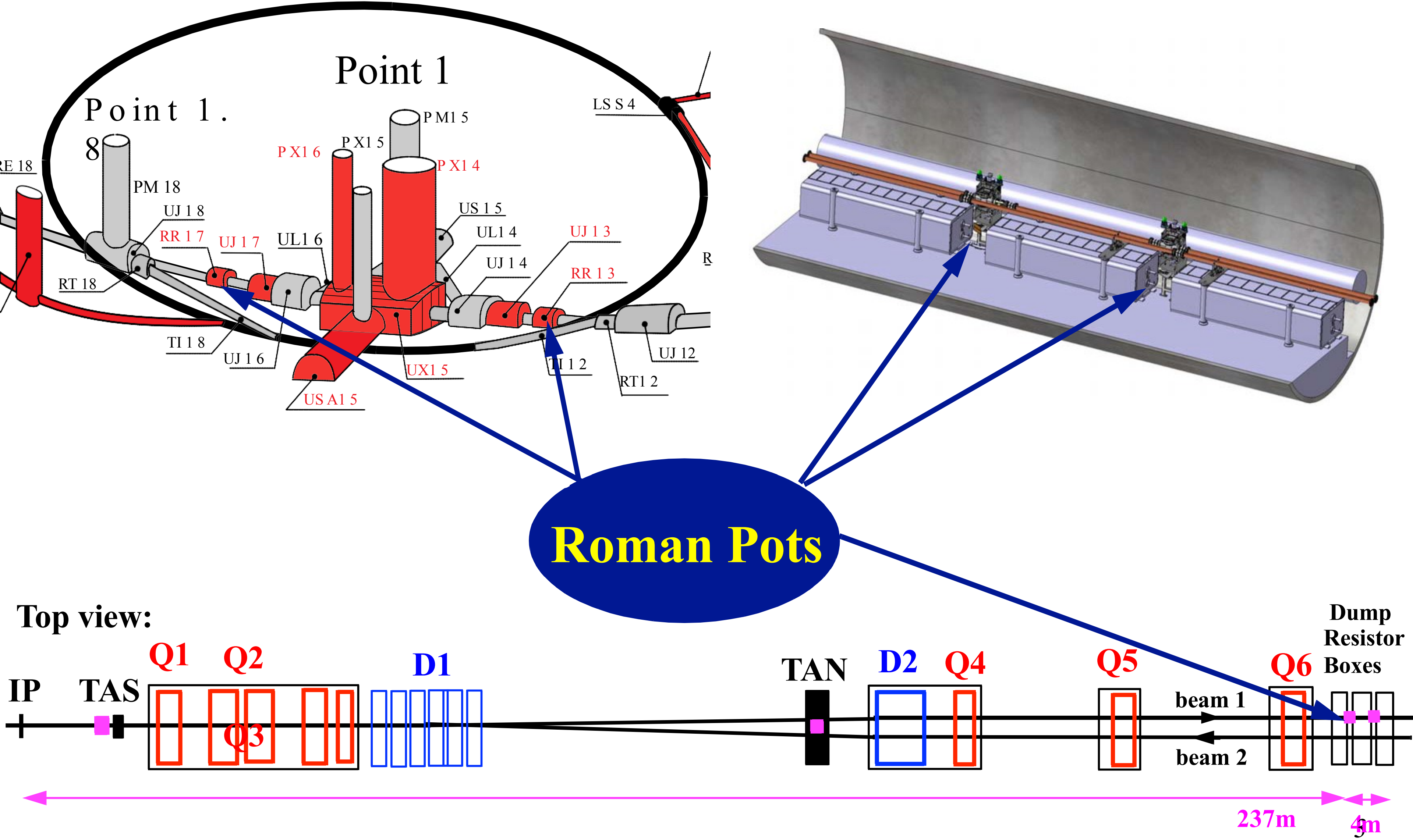
T = 3.5 Prad





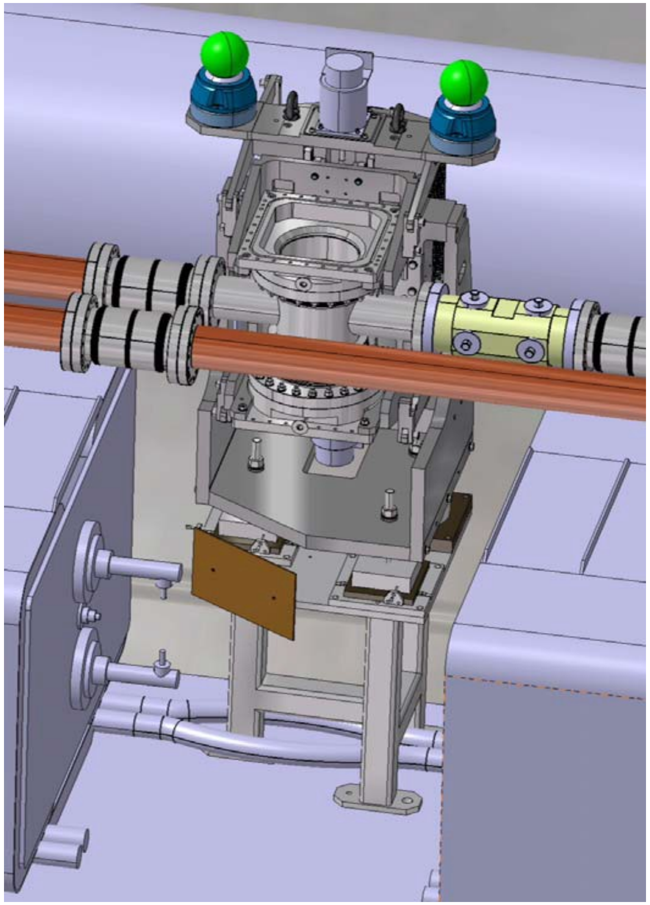
Location of ALFA

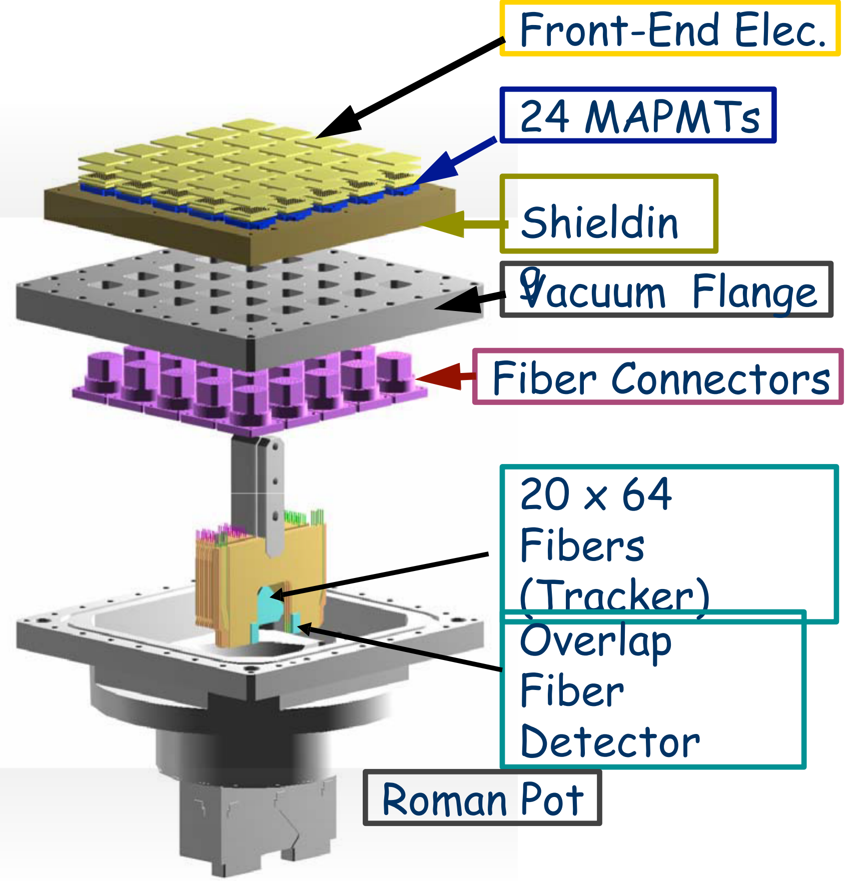
ALFA: Absolute Luminosity For Atlas



The Roman Pots

The Roman Pot Unit





Front-End Elec.

24 MAPMTs

Shieldin

Vacuum Flange

Fiber Connectors

20 x 64 Fibers (Tracker)

Overlap Fiber Detector

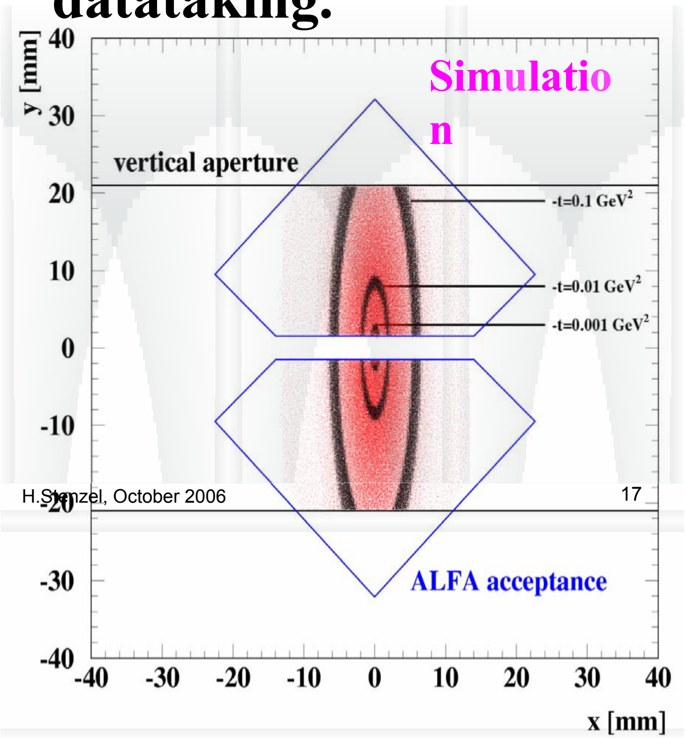
Roman Pot

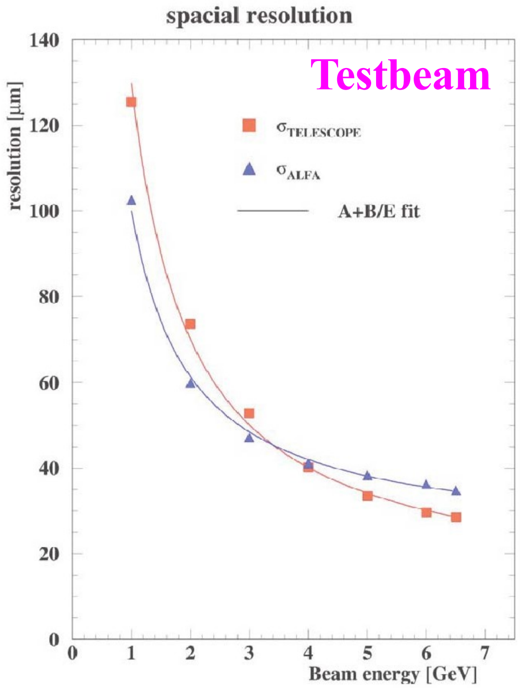
The Fibre Tracker

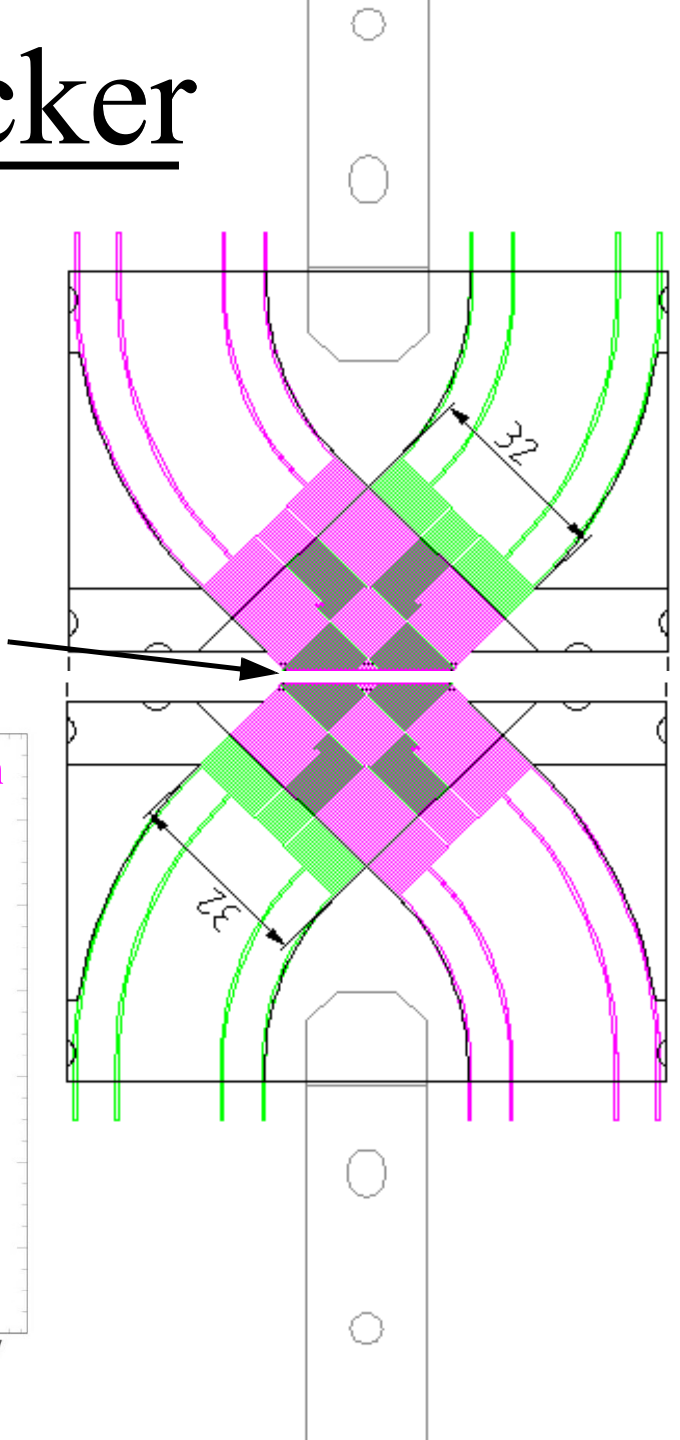
The tracker is made of 0.5 mm^2 square scintillating fibres.

These are arranged in 10 U- and 10 V-planes with 64 fibres in each plane.

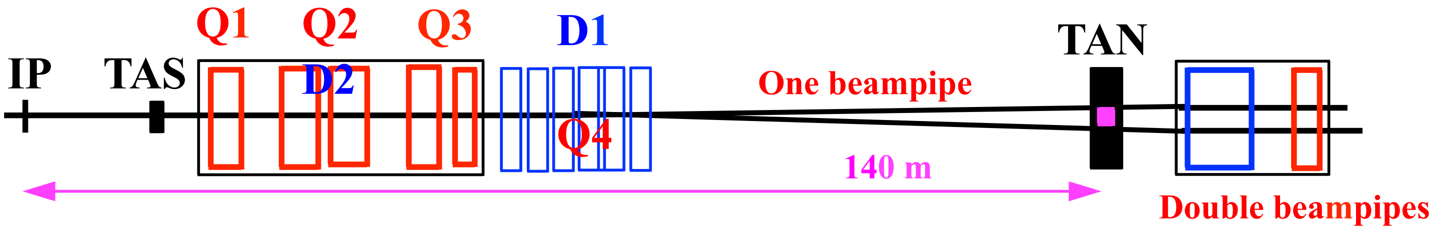
The distance between the top and bottom detector is only about 3 mm during datataking.





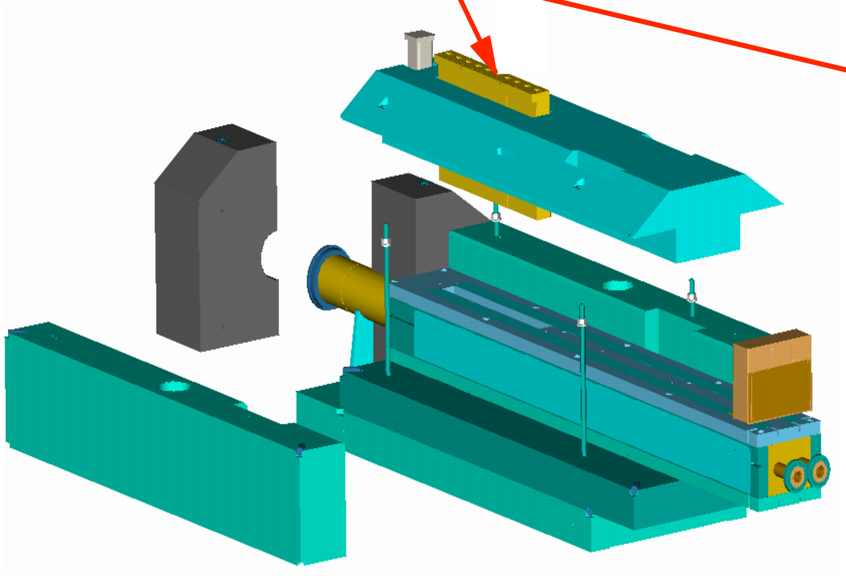


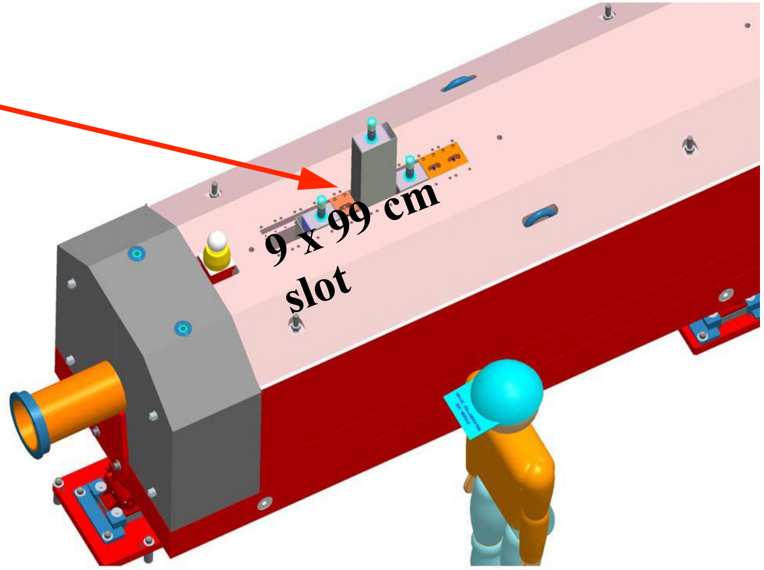
ZDC - Zero Degree Calorimeter



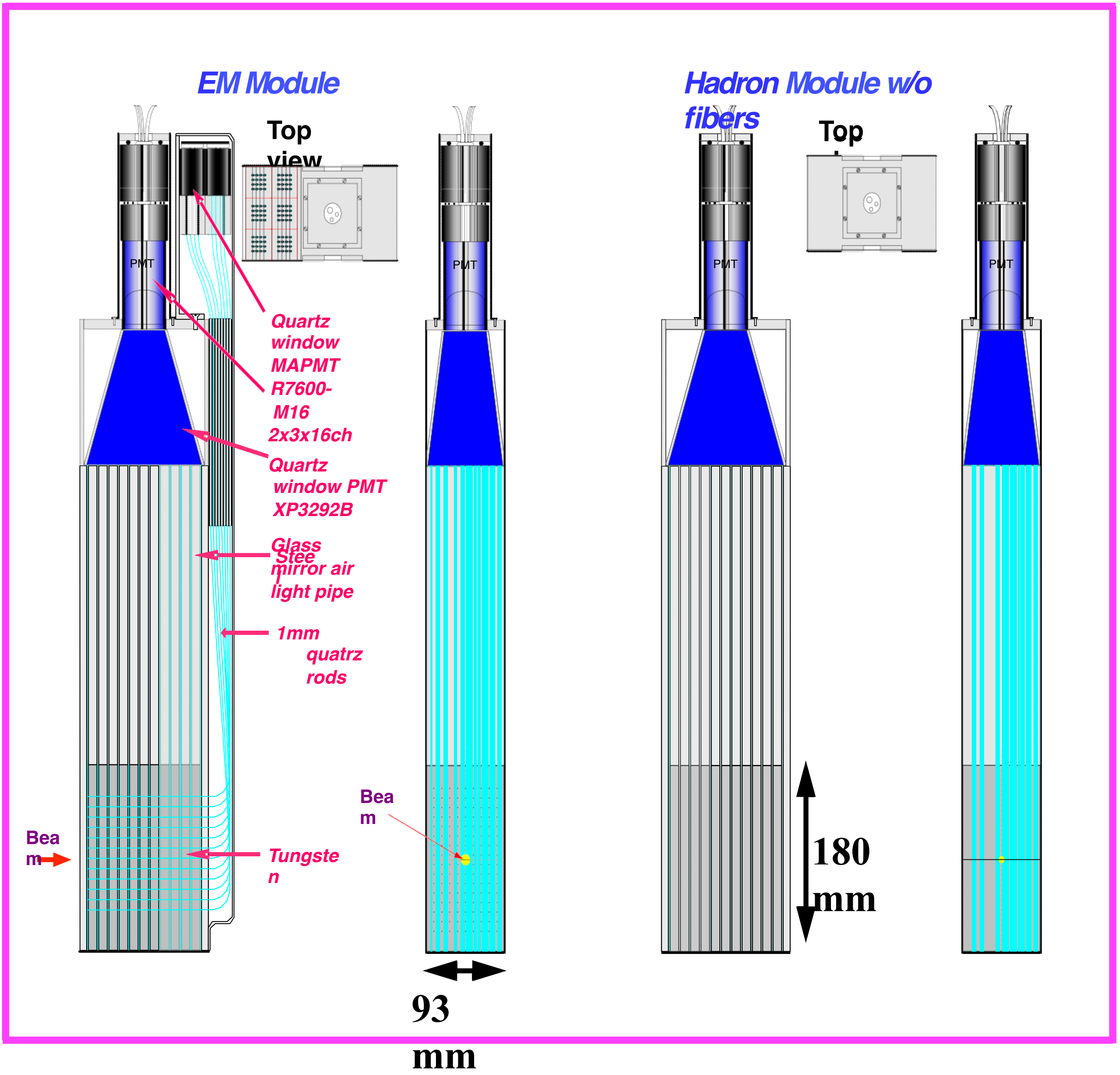
The Zero Degree Calorimeter will measure forward neutral particle production and it will be used for centrality measurements in heavy ion collisions (and for luminosity measurements in pp).

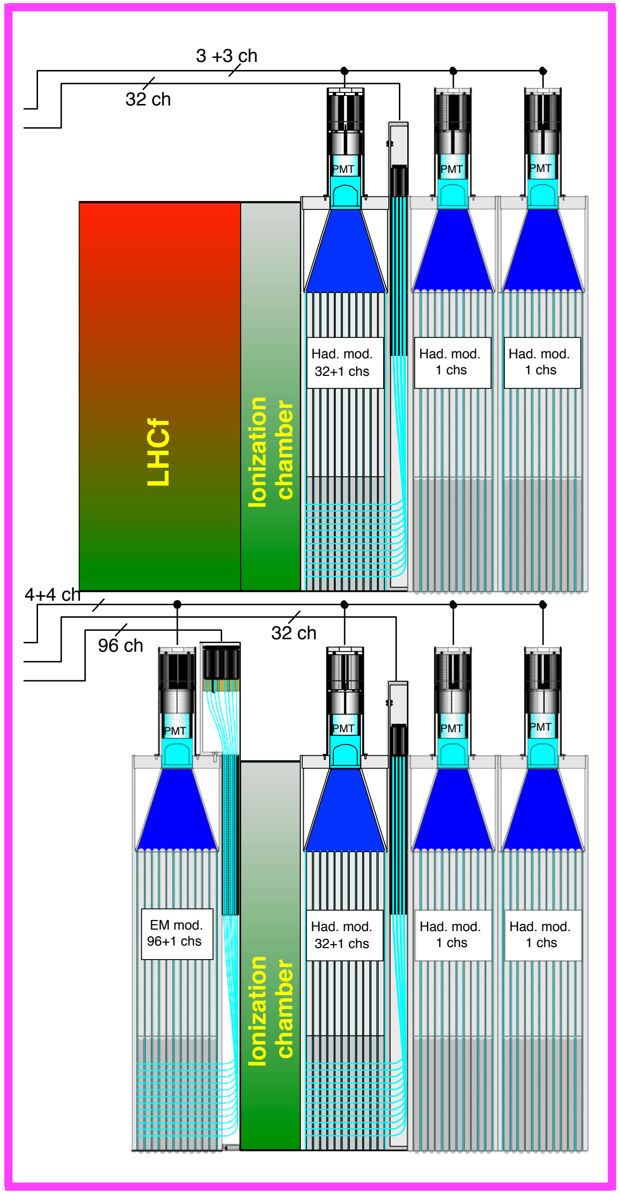
The ZDC sits in a slot in the TAN (which protects the magnets behind it from radiation).





The Calorimeter Modules



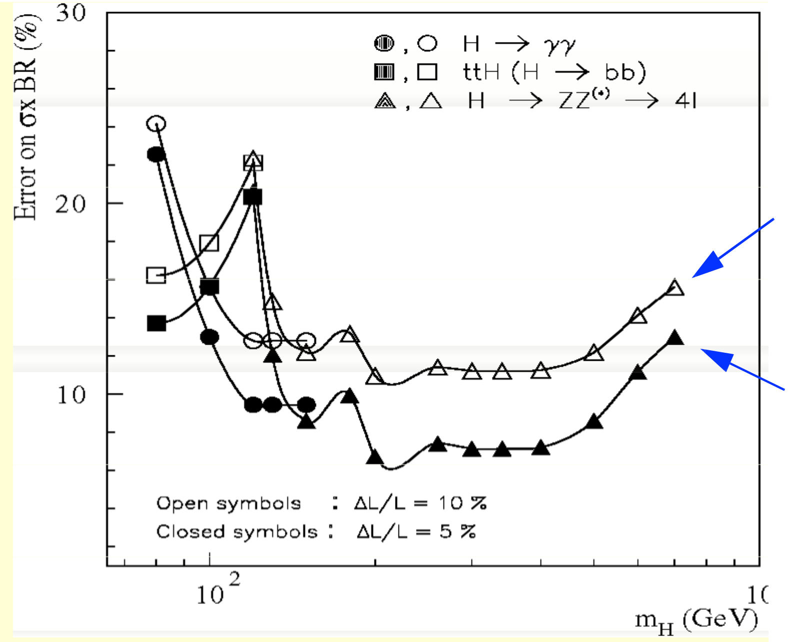


Luminosity determination

WHY ?

Example →

Higgs coupling



$$\frac{\Delta L}{L} = 10\%$$

$$\frac{\Delta L}{L} = 5\%$$

STRATEGY ?

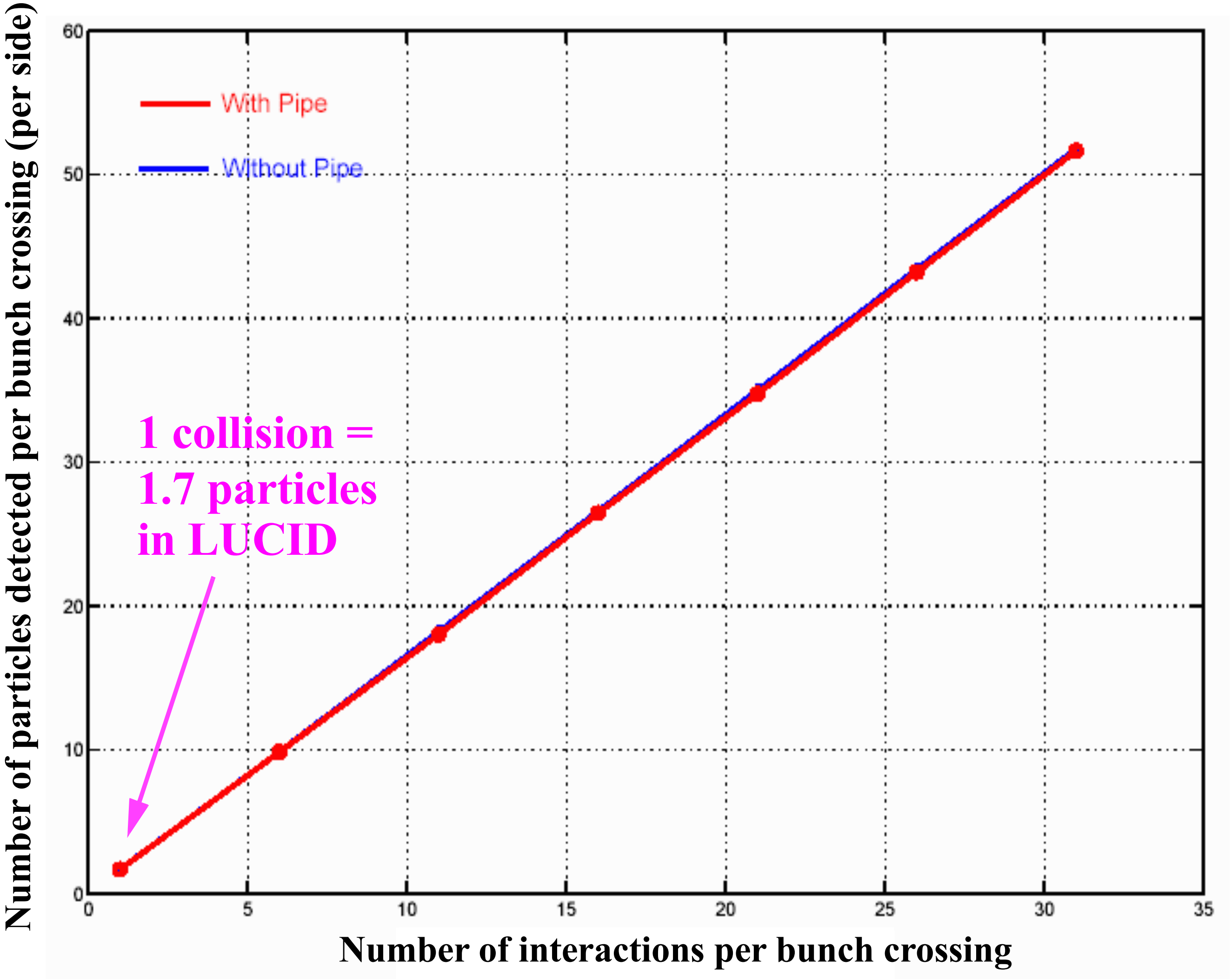
Measure elastic scattering at low luminosity
Measure rates of well-calculable processes e.g. QED, QCD Measure relative luminosity with luminosity monitors

GOAL ?

Measure the luminosity with 2-3% accuracy

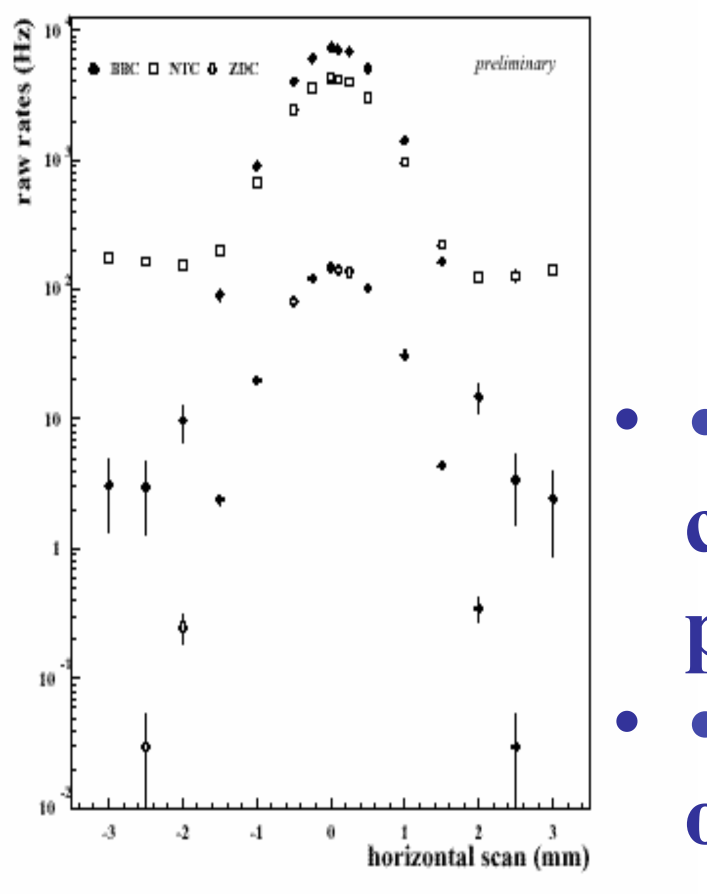
LUCID: Principle

Simulations shows a perfectly linear relationship between the number of particles measured in LUCID and the luminosity.



1 collision = 1.7 particles in LUCID

ZDC: Luminosity in pp

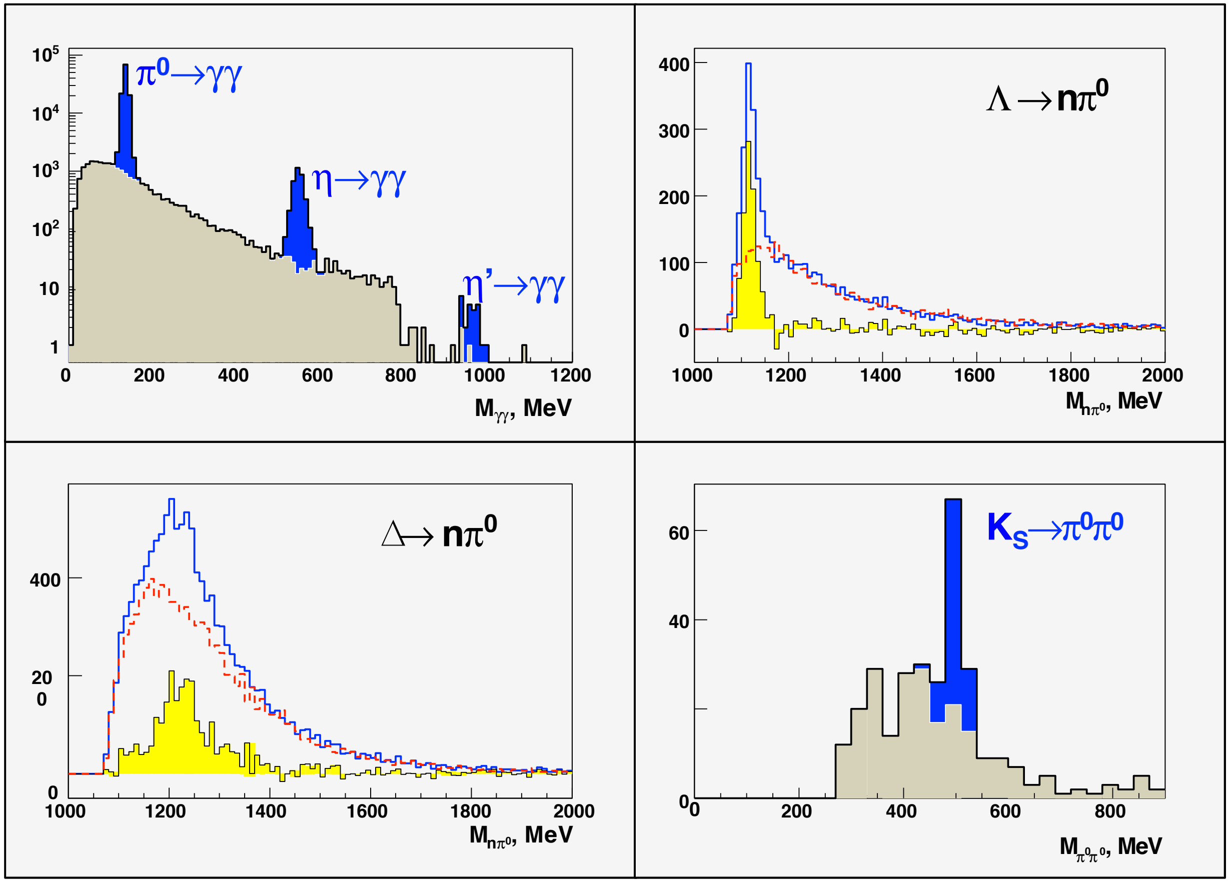


- RHIC ZDC as an accelerator tool (in pp)

- •Van derMeer scan (ZDC coincidence rate vs. relative beam position)
- •ZDC (lower curve) bkg free over 4 orders of magnitude

ZDC: Measurements in pp

In pp, the ZDC can measure forward production cross sections for several types of particles at very high energies. This will be useful for adjusting parameters for simulations and models, and for cosmic ray physics where the energy in one proton's rest frame is 10^{17} eV – a very interesting energy for extended air showers.

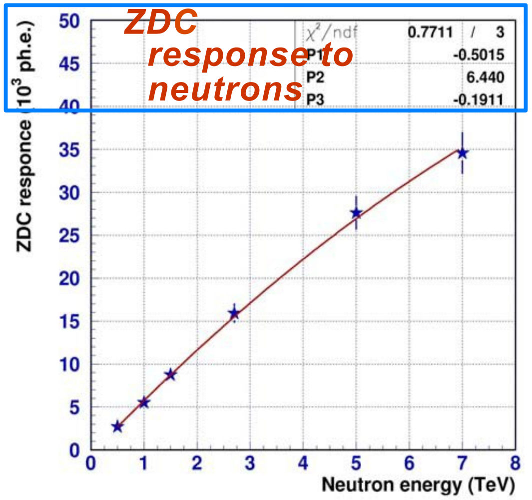


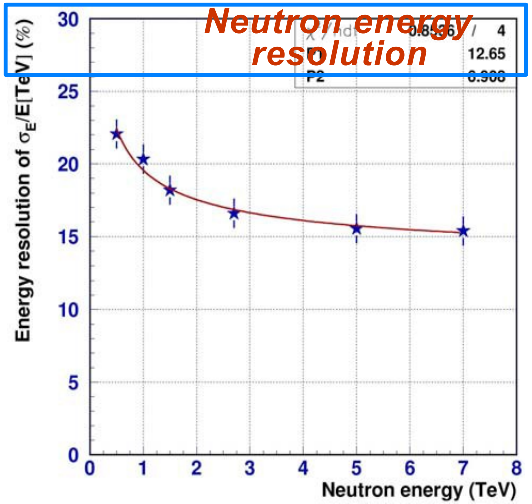
What happens when a high energy proton hits the upper atmosphere?

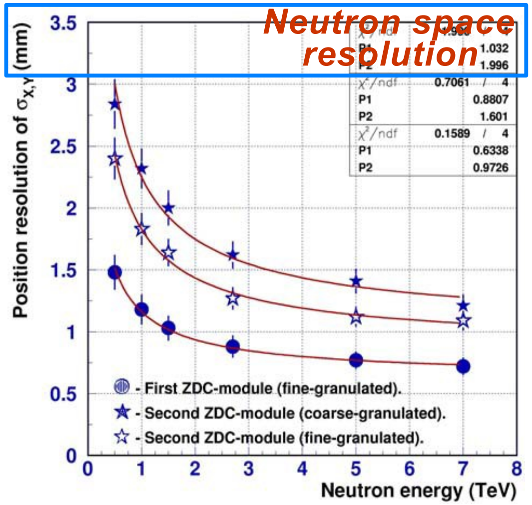
The ZDC can find a pi0 in the midst of several neutrons.

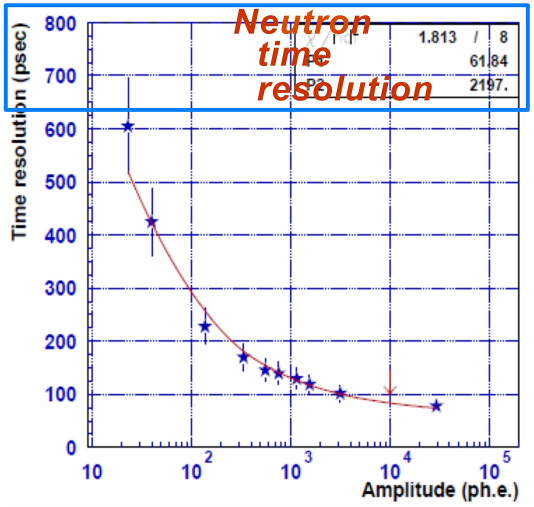
(1M Pythia events analyzed by a ZDC)

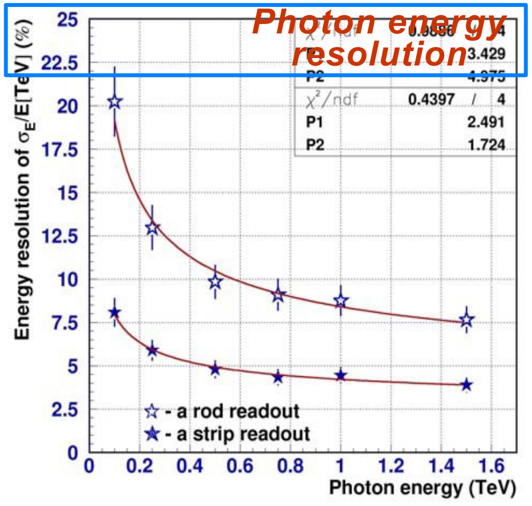
ZDC time, space and energy resolution (Average over active area)

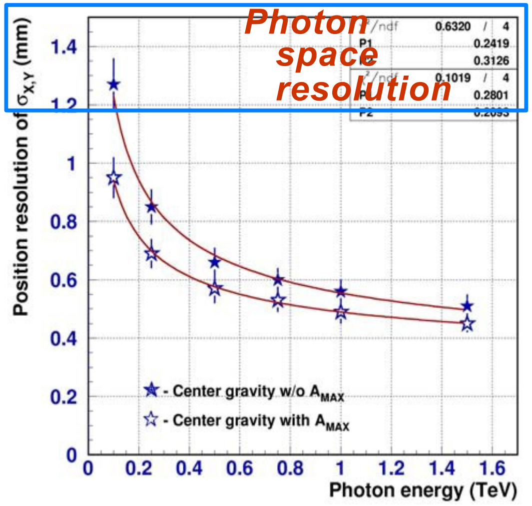

ZDC response to neutrons


Neutron energy resolution

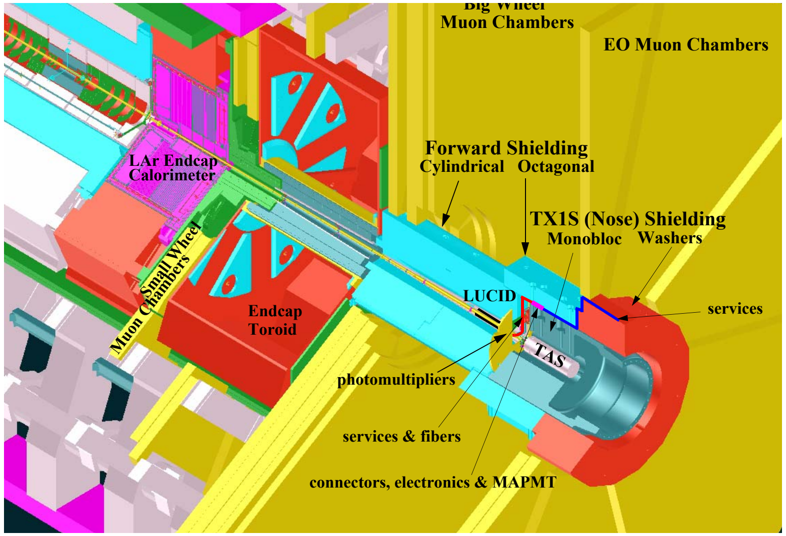

Neutron space resolution

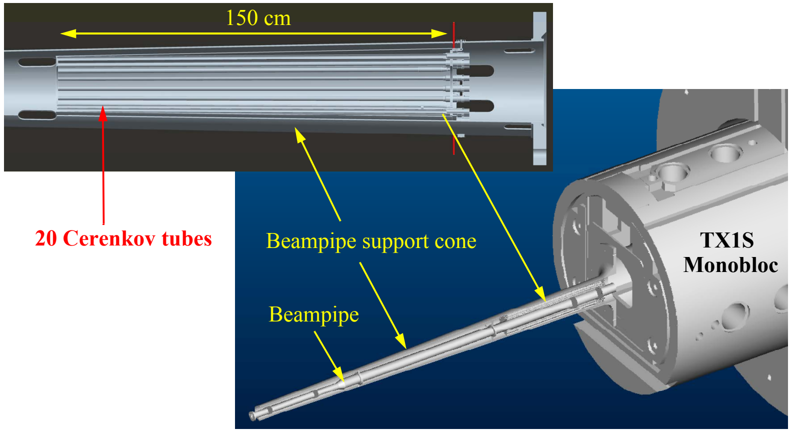

Neutron time resolution


Photon energy resolution


Photon space resolution

LUCID Detector





The LUCID detector surrounds the beam pipe on both sides of the interaction point at a distance of 17 m. Each LUCID vessel contains 20 Cherenkov detectors (1.5 m long) consisting of aluminum tubes with 15 mm diameter pointing towards the interaction region. The gas in the detector is C_4F_{10} at 1.1-1.5 bar pressure. The Cherenkov light is collected in 16 of the tubes at the back by 15 mm diameter photomultipliers. These photomultipliers have quartz windows to make them more radiation hard than normal photomultipliers. In 4 of the tubes the light is collected by a cone and then transmitted by optical quartz fibers to the outside of the Forward Shielding. Quartz fibers are used since they are more radiation-hard than plastic fibers.

Luminosity measurements in ATLAS: offline

MBTS_1 with Δt cut

- $2.1 < |\eta| < 3.8$
- $|\Delta t_{A\text{-}C}| < 10$ ns to eliminate beam halo & distant beam-gas
- very similar to online MBTS_event_AND, but
  - better background rejection
  - bunch-by-bunch capability

LAr-based event counting

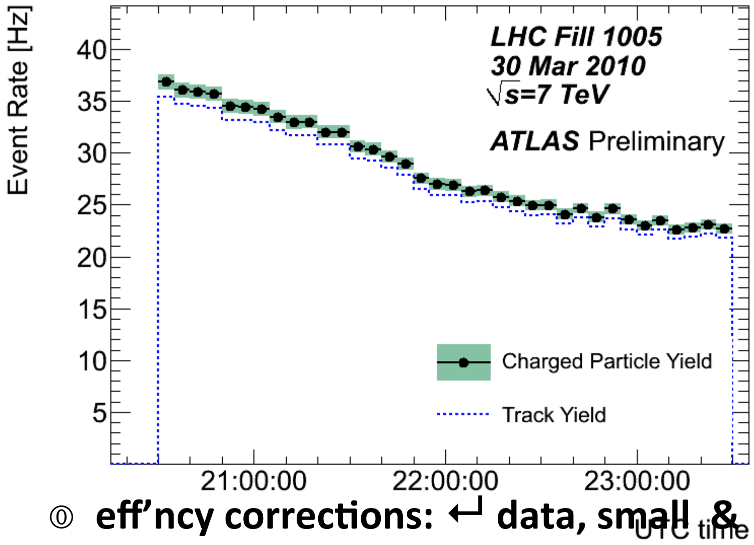
- $2.5 < |\eta| < 4.9$
- ≥ 2 cells above 0.25 (1.2) GeV in EMEC (FCAL) on both A&C sides
- $|\Delta t_{A\text{-}C}| < 5$ ns

Primary-vertex counting

- reconstructed vertex with ≥ 2 good-quality tracks of $p_t > 0.1$ GeV/c
- track & vertex selection as in charged-multiplicity analysis

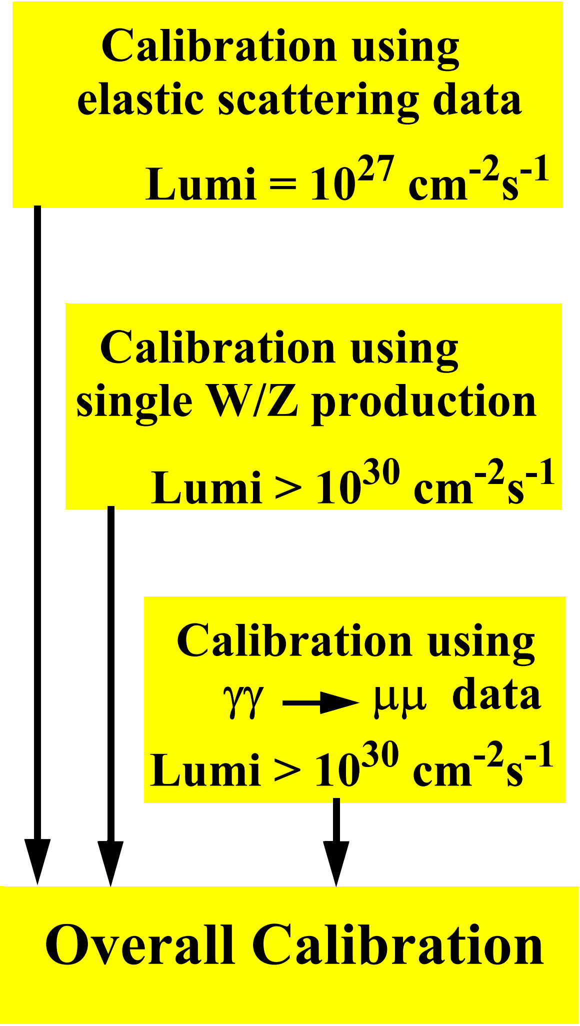
Charged-particle-based event counting

- goal: comparison of Collision Rate in ALICE, ATLAS & CMS
- counts events with
  - ✓ $n = 1$ track: $p_t > 0.5$ GeV/c, $\eta < 0.8$ consistent w/ a good prim. vertex



- eff'ncy corrections: ↵ data, small & well understood: $(4 \pm 1.7\ \%)_{syst}$

Calibration & Dynamic Range



Calibration using elastic scattering data

Lumi = 10^{27} cm^{-2}s^{-1}

Calibration using single W/Z production

Lumi > 10^{30} cm^{-2}s^{-1}

Calibration using $\gamma\gamma \rightarrow \mu\mu$ data

Lumi > 10^{30} cm^{-2}s^{-1}

Overall Calibration

Lumi = 10^{27} cm^{-2}s^{-1} → 10^{34} cm^{-2}s^{-1} A factor 10^{7} !

At 10^{27} there will be 2×10^{-4} interactions/bunch → 1.7 part./inter.

At 10^{34} there will be 20 interactions/bunch → 33 part./bunch

The rate of $W \rightarrow l\nu$ is expected to be 60 Hz at high luminosity

The uncertainty in the rate of W/Z events is currently about 4%

CDF is also using the process $W \rightarrow l\nu$ for absolute normalization

QED process

The muons are centrally produced with small acoplanarity

About 10k events/day at high lumi if $P_T > 3$ GeV (1.5k if $P_T > 6$ GeV)

Absolute $\mathcal{L}$ Calibration by beam-separation scans: principle

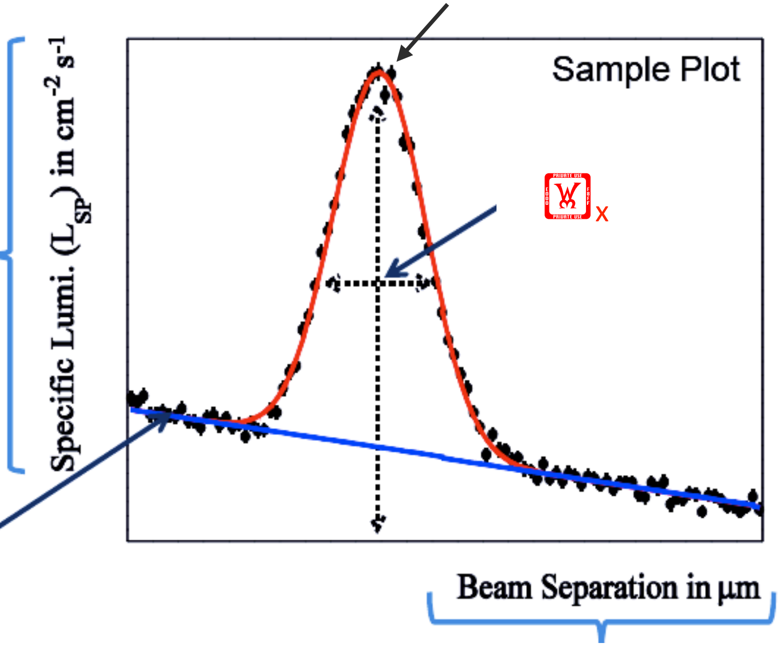
Principle: measure simultaneously

$\mathcal{L} = f\ (I_1, I_2, S_x, S_y)$

R_{max} = peak collision rate (arb. u.)

From HF, vtx counting, LUCID, MBTS, ZDC ...

$R_{max} \sim \mathcal{L}\ □_{inel}\ □_{det}$



Background

$s_{vis} = R_{max} / \mathcal{L}$

$□ s_{vis}/s_{vis} \sim □ I_{1,2}\ □□ I_{1,2}$

$\sim □□_{x,\,y}\ □□□_{x,\,y}$

$\sim □ R_{max}\ □□ R_{max}$

$$\mathcal{L} = \frac{n_b f_r I_1 I_2}{2\pi\Sigma_x\Sigma_y}$$

Simplest case: $□□_x = (s^2_{1x} + s^2_{2x})^{1/2}$

Luminosity from W & Z counting

- Leptonic decay channels provide very clean experimental signature
  - robust against pile-up + reasonable statistics: good <u>relative</u> $\mathcal{L}$ monitor
    - *s (W → ln)* ~ 9-10 nb, $<e>_{e,\,m}$ ~ 34 % (ATLAS, ICHEP'10)
    - $\mathcal{L}$ ~ 1-2 10^{32} cm^{-2} s^{-1} i.e. 4 pb^{-1}/day ➔ 25 K evts/day (using *e* + *m*)

- Constantly increasing precision of QCD calculations makes W/Z counting a possible way of measuring <u>absolute</u> luminosity

$$\mathcal{L} = (N - BG)/ (A_W * C_W * □_{th})$$

$\mathcal{L}$ is the integrated luminosity
N is the number of W/Z candidates
BG is the number of background events
A_W is the geometrical + kinematical acceptance
C_W is the letpon (+ E_T^{miss}) reconstruction efficiency
$□_{th}$ is the theoretical inclusive cross section

Luminosity from W & Z counting: a rough guess at systematics

$$\mathcal{L} = (N - BG)/(A_W * C_W * □_{th})$$

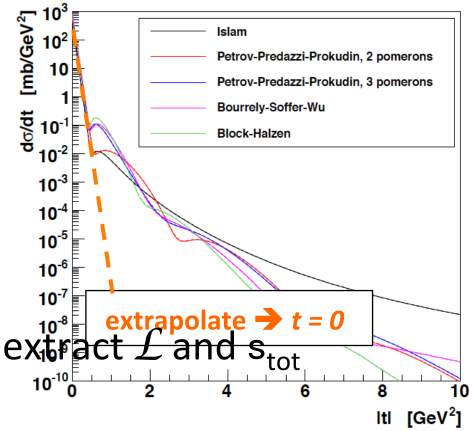
s_{vis}

	Precision now	**Precision in 2-3 years (?)**	**Comments**
s_{th} (m_R, m_F)	< 1%	< 1%	Scale uncertainty at NNLO (Anastasiou et al., PRD 69, 94008)
PDF → s_{th}	4-5 %	3-4 % ?	Constrain PDF's using LHC data?
DC_W / C_W	7-8 %	2 % ?	Large improvements expected with more Z's (tag-&-probe). CDF achieved 2 %
DA_W / A_W	3 %	2% ?	Constrain PDF's using LHC data?
Total	**9-10 %**	**4-5 %?**	Long-term dominated by PDF

Elastic *pp* scattering and luminosity: optical theorem + …

- … total *pp* rate (TOTEM; ALFA)
  - s$_{tot}$ related to forward amplitude

    s$_{tot}$ = 4p Im f$_{el}$(0)
  - measure <u>simultaneously</u>
    - total interaction rate $N_{inel} + N_{el}$
    - differential elastic rate dN_{el}/dt



$|t| \sim p_B^2\, q^2$

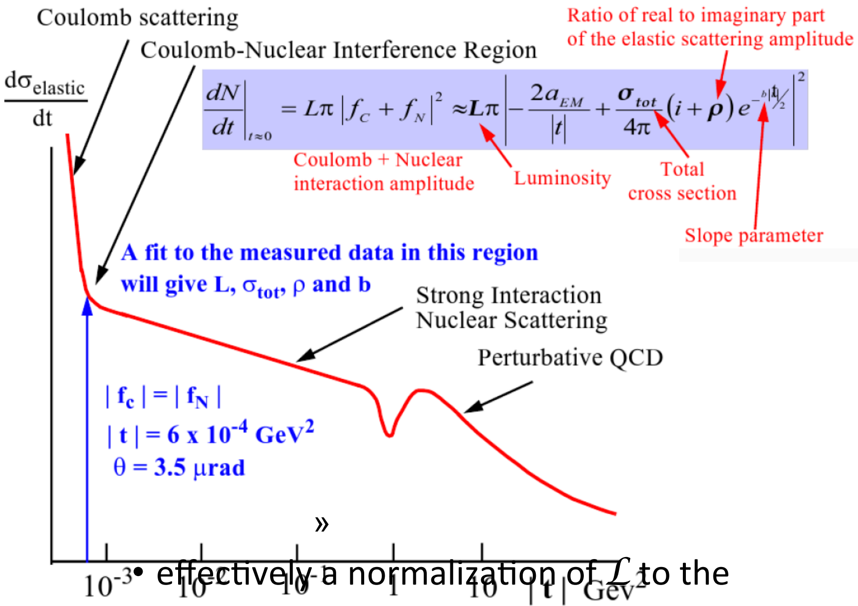
  - extract ℒ and s$_{tot}$

$$\mathcal{L}\,\sigma_{\rm tot} = N_{\rm el} + N_{\rm inel}$$

$$\mathcal{L}\,\sigma^2_{\rm tot} = \frac{16\pi}{1+\rho^2}\cdot\left.\frac{dN_{\rm el}}{dt}\right|_{t=0}$$

(r from theory; error on ℒ small bec. 1+r²)

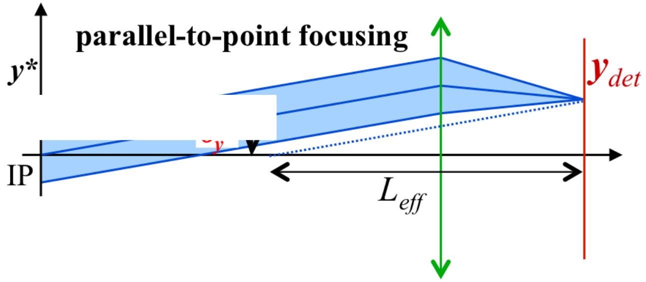
- … Coulomb interference (ALFA)
  - Measure at such small *t* - values that s$_{el}$ becomes sensitive to the Coulomb amplitude



- effectively a normalization of ℒ to the exactly calculable QED amplitude
- no total-rate measurement ➔ no add'tl detectors needed to cover ☒ ☒ 5
- used by UA4: ℒ to 2-3 %

Elastic scattering: experimental requirements for TOTEM / ALFA

- Very demanding beam conditions: need to reach q_{scat} ~ 6 (3) mrad
  - tiny angular divergence: $s^*_q = \surd e/b^*$ must be << q_{scat}
  - very small emittances: e_{inv} ~ 1 mm (nominal = 3.75 mm)
  - large b*: 90m, then 1540 m (TOTEM); 2600 m (ALFA)
  - parallel-to-point focussing
    - DQ^*_y ➔ Dy_{det}
    - Dy^* ➔ 0 @ det

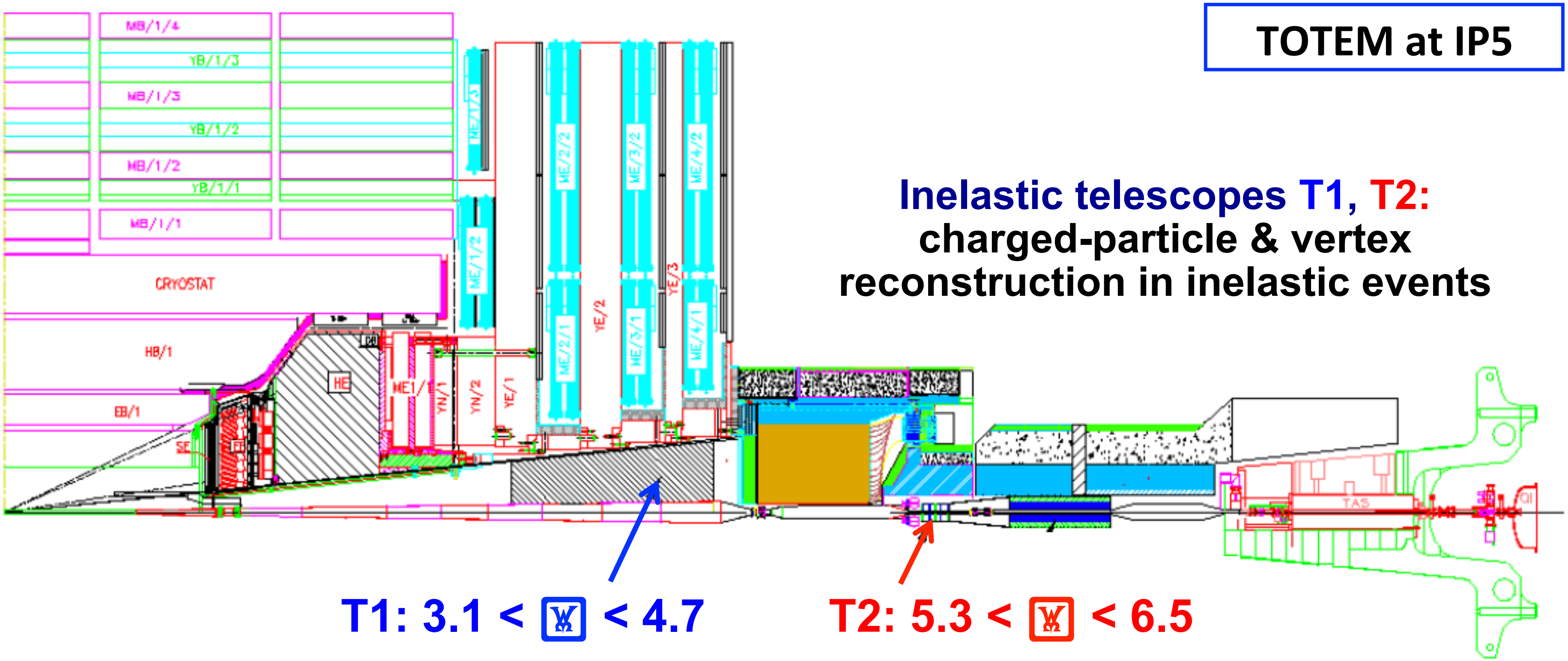


  - zero crossing angle ➔ < 156 bunches ➔ low $\mathcal{L}$ (10^{27-29} cm^{-2} s^{-1})

- Detector able to approach the beam within 1 – 1.5 mm (10-12 s)
  - extremely precise, ‘edgeless’ detectors: Si (TOTEM), Sci fibers (ALFA)
  - compact electronics
  - Roman Pots with precision mechanics to approach the beam
  - exquisite control of alignment: detector-to-detector, beam-to-detector

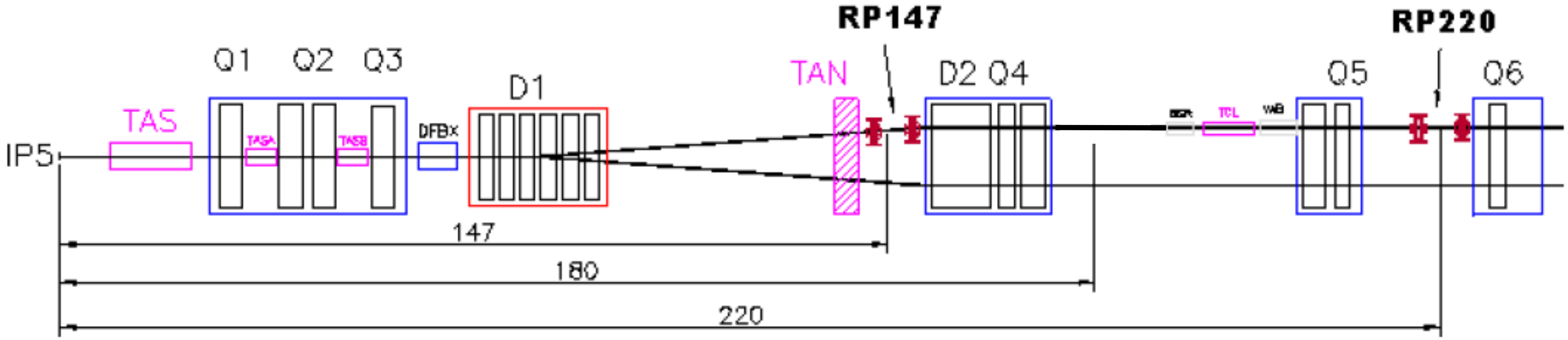
TOTEM at IP5

Inelastic telescopes T1, T2:
charged-particle & vertex reconstruction in inelastic events



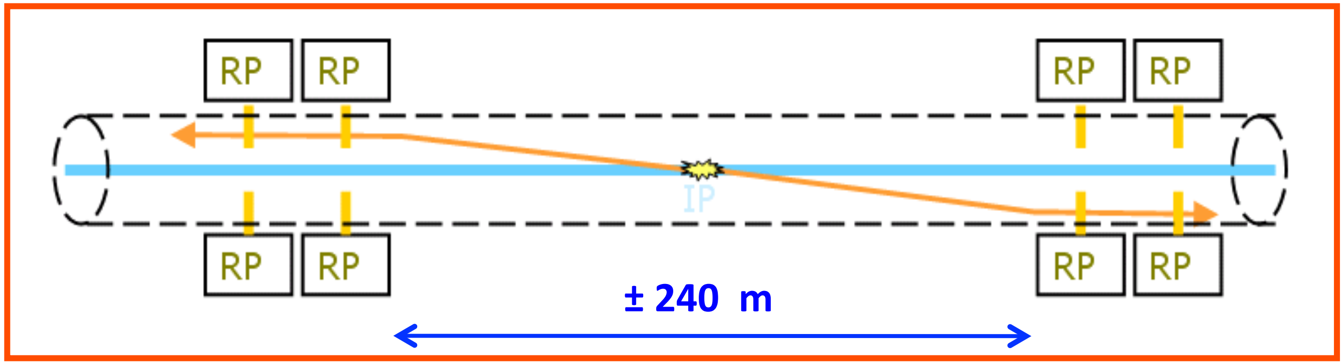
T1: $3.1 < \eta < 4.7$

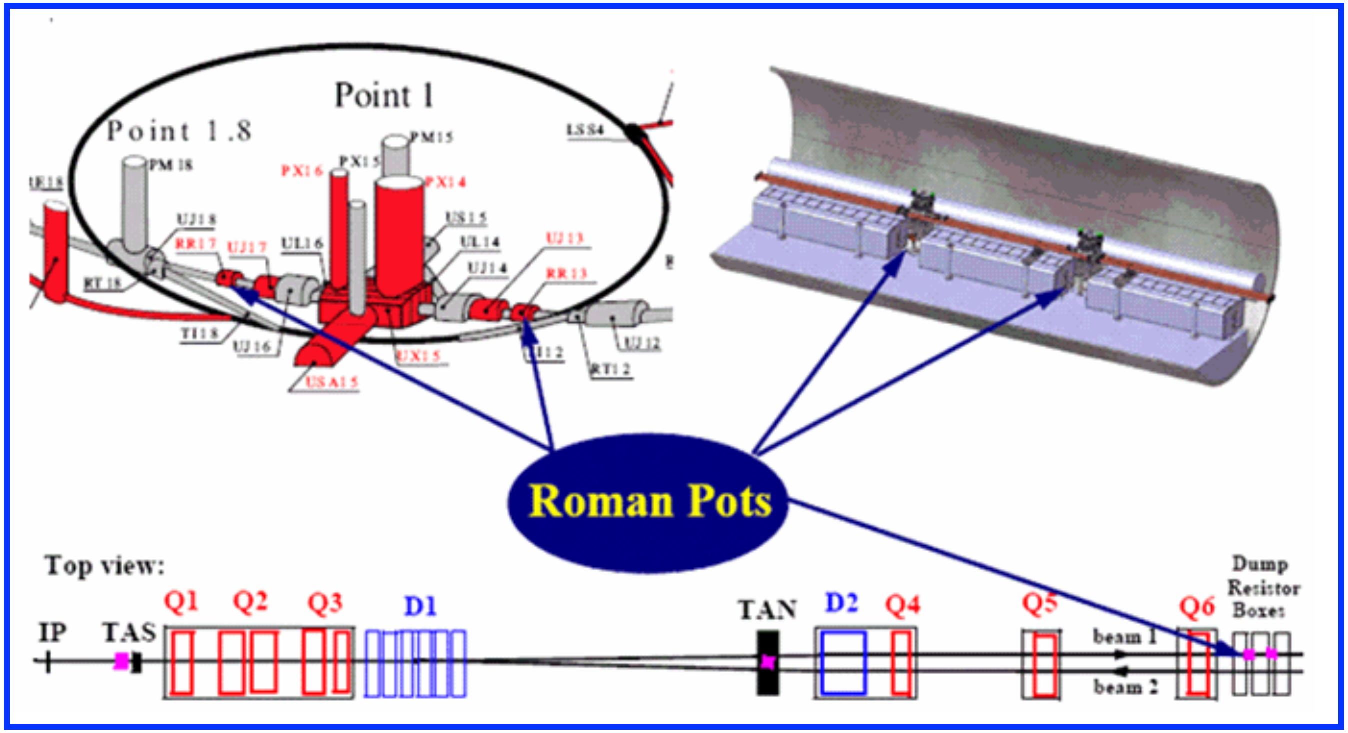
T2: $5.3 < \eta < 6.5$

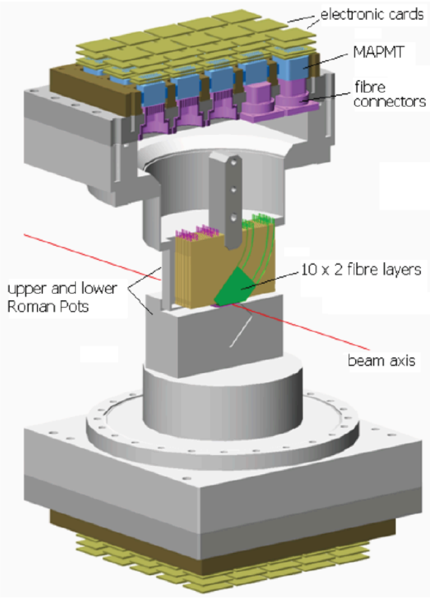


LHC beam line on one side of interaction point IP5 and the TOTEM Roman Pots at distances of about 147m (RP147) and 220m (RP220).

Absolute Luminosity For ATLAS







Elastic scattering: precision prospects

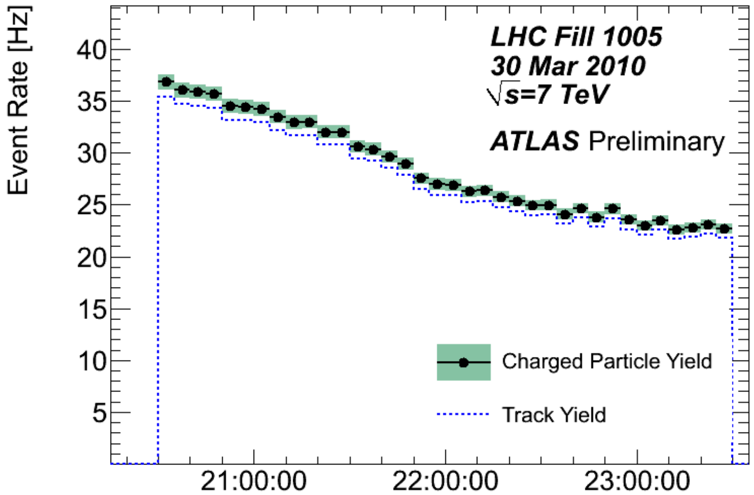
- Optical theorem + total rate
  - Measurements of the total rate in combination with the *t*-dependence of the elastic cross section is a well established and potentially powerful method for luminosity calibration and measurement of □$_{tot}$
  - Estimated TOTEM systematics on absolute $\mathcal{L}$: 2-4 % (@ b* = 1540). Mainly:
    - extrapolation to t = 0
      - b* = 90 m: ± 5-6 %
      - b* = 1540 m: □ 1 % (theoretical) (+) 1 - 4 % (machine optics)
    - total inelastic rate ~ 0.8 % □ ± 1.6 % in luminosity
    - □: ± 1.2 % on $\mathcal{L}$
- Optical theorem + Coulomb interference (ALFA)
  - Main challenge not the detectors but rather the required beam properties
    - Will the optical properties of the beam be known to the required precision?
    - Will it be possible to decrease the emittance as much as we need?
    - Will the beam halo allow approaching in the mm range?
  - No definite answers before we try…
    - UA4 achieved a precision using this method at the level of 2-3 % but at the LHC it will be harder .....

Luminosity measurements in ATLAS: offline (1)

- **MBTS_1 with ☒t cut**
  - 2.1 < |☒| < 3.8
  - trigger = MBTS_1 (OR) on paired BX (colliding bunches only)
  - |☒t_{A-C}| < 10 ns to eliminate beam halo & distant beam-gas
  - very similar to online MBTS_event_AND, but
    - better background rejection
    - bunch-by-bunch capability
  - ☒ = 80.6 % at 7 TeV (Pythia 6)

- **Primary-vertex counting**
  - reconstructed vertex with ☒ 2 good-quality tracks of p_t > 0.1 GeV/c
  - track & vertex reconstruction cuts as in charged-multiplicity analysis @ 7 TeV
  - ☒ = 81.0 % at 7 TeV (Pythia 6)

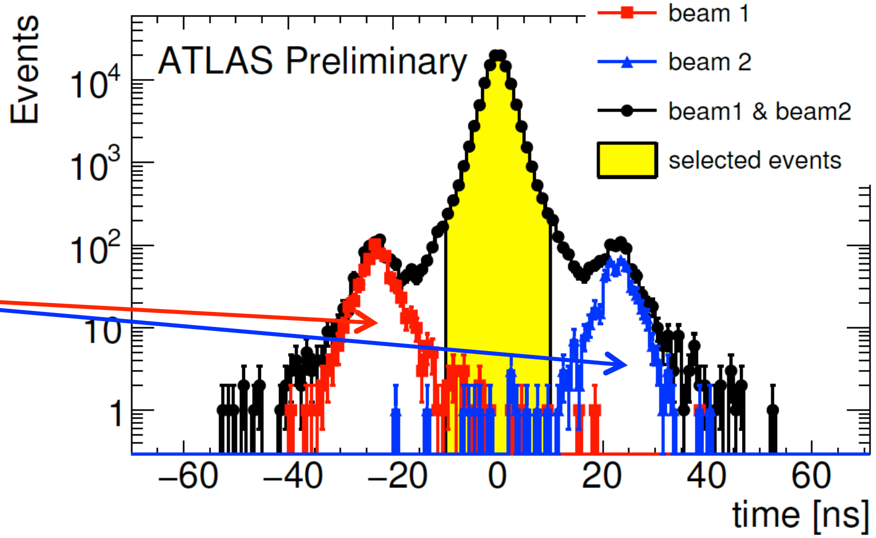
- **Charged-particle-based event counting**
  - goal: comparison of Collision Rate in ALICE, ATLAS & CMS
  - trigger = MBTS
  - counts events with
    - ✓ ☒ 1 track: p_t ☒ 0.5 GeV/c, |☒| < 0.8 consistent w/ a good prim. vertex



  - eff'ncy corrections: ↵ data, small & well understood: (4 ± 1.7 %)$_{syst}$
  - ☒ = 63.8 % at 7 TeV (Pythia 6)

Luminosity measurements in ATLAS: offline (2)

- **MBTS_1 with ⊠t cut**
  - $2.1 < |⊠| < 3.8$
  - trigger = MBTS_1 (OR) on paired BX (colliding bunches only)
  - $|⊠t_{A\text{-}C}| < 10$ ns to eliminate beam halo & distant beam-gas
  - very similar to online MBTS_event_AND, but
    - better background rejection
    - bunch-by-bunch capability
  - ⊠ = 80.6 % at 7 TeV (Pythia 6)



- **LAr-based event counting**
  - $2.5 < |⊠| < 4.9$
  - trigger = MBTS_1 (OR), paired BX
  - ⊠ 2 cells above 0.25 (1.2) GeV in EMEC (FCAL) on both A&C sides
  - $|⊠t_{A\text{-}C}| < 5$ ns
  - ⊠ = 72.6 % at 7 TeV (Pythia 6)

Charged-particle based event counting (1)

Events are required to have:

- good primary vertex
- triggered by the MBTS
- At least one track with p_T>500 MeV/c; $|\eta|<0.8$, consistent with the primary vertex

Correction procedure:

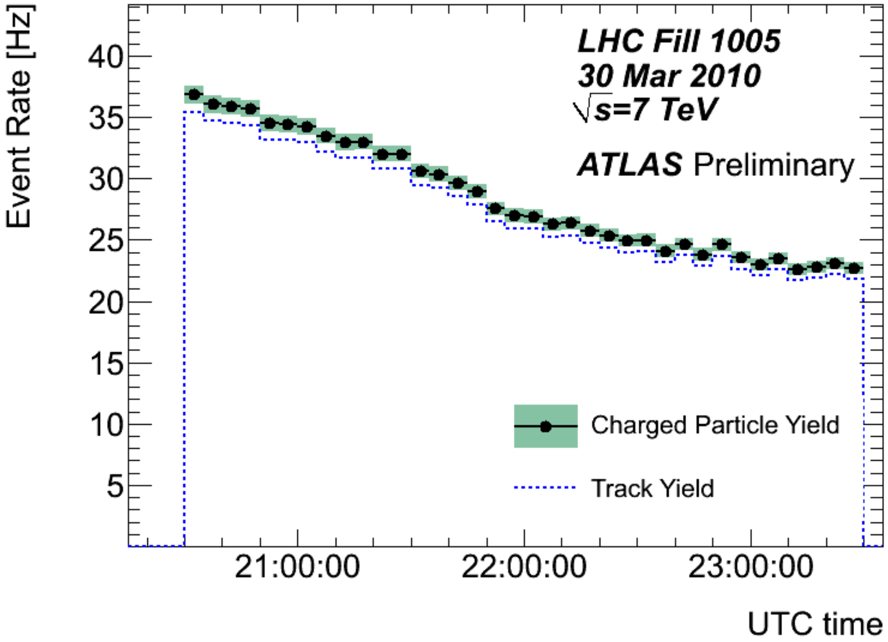
- Each event is given a weight to account for trigger and vertex inefficiencies (derived from data)
- MC derived matrix is used to correct observed number of tracks in event to number of charged particles produced
- Corrected number of charged particles distribution is used to correct for event loss due to tracking inefficiency by the following bin weight

$$C(n_{ch}) = \frac{1}{1-(1-\langle\varepsilon\rangle)^{n_{ch}}}$$

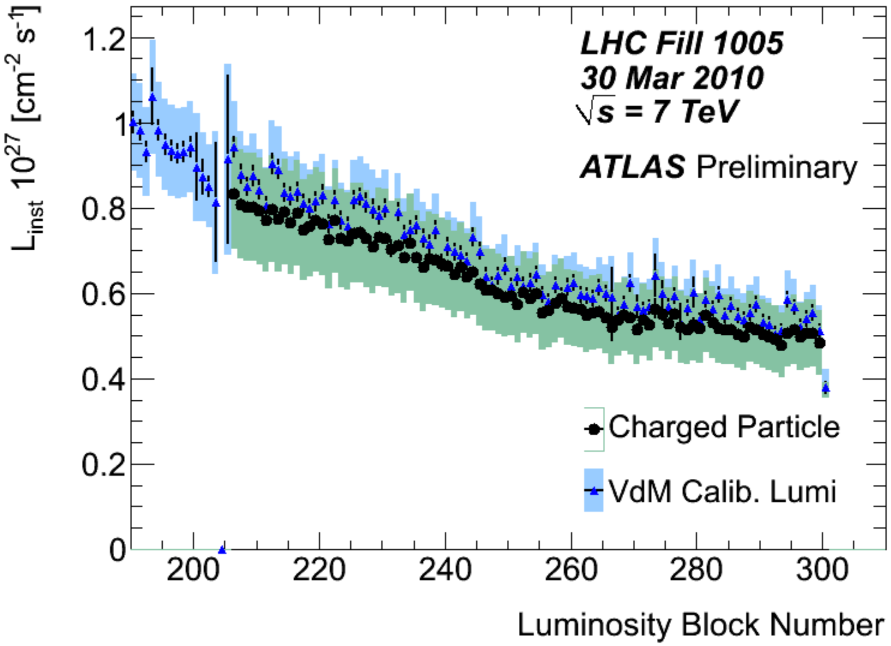
Where <ε> is the avg. tracking efficiency and n_{ch} is the number of charged particles

- The N_{ch} distribution is then integrated to obtain the total number of events.

Charged-particle based event counting (2)



Rate of events in LHC Fill 1005 with at least one charged primary particle with pT>0.5 GeV/c, |eta|<0.8, versus UTC time (solid markers). Also shown is the raw rate of events with at least one track in this acceptance range (dashed line). The correction factor applied to the raw rate to obtain the charged particle rate is 1.04 +\- 0.017. Error bars represent the statistical uncertainty, the colored bands include both the systematic and statistical uncertainties.

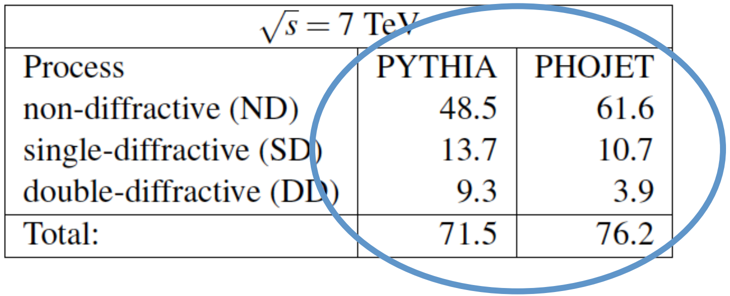


Instantaneous luminosity derived from counting of events with at least one charged primary particle (pT>0.5 GeV/c, |eta|<0.8) for Fill 1005 as a function of time (black points) compared with the Van der Meer calibrated ATLAS luminosity measurement (blue triangles). Pythia MC09 was used for the acceptance and cross-section models for the charged particle analysis. Error bars represent the statistical uncertainty; the colored bands include both the systematic and statistical uncertainties. The systematic uncertainties on the charged particle method account for the correction procedure and the dependence on the MC models used for the acceptance and cross-sections by comparing the results obtained with Pythia MC09 & Phojet.

Monte-Carlo based $\mathcal{L}$ normalization: main issues

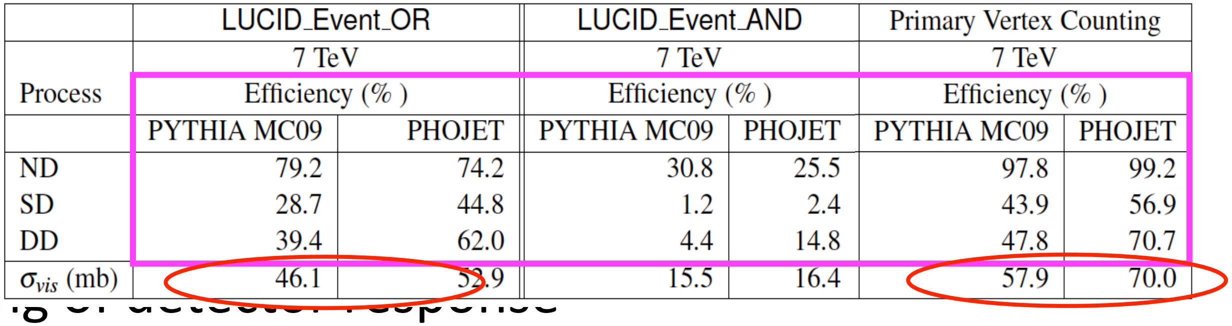
$$\mathcal{L}dt = \frac{\mu^{meas} n_b f_r}{\sigma_{vis}} = \frac{\mu^{meas} n_b f_r}{\boxed{\varepsilon}_{ND}\sigma_{ND}+\boxed{\varepsilon}_{SD}\sigma_{SD}+\boxed{\varepsilon}_{DD}\sigma_{DD}}$$

- Physics uncertainties **+- 20%**
  - no measurements of σ_{inel} exist @ 7 TeV
  - contribution of non-, single- & double-diffractive cross-sections poorly known



$\sqrt{s} = 7$ TeV		
Process	PYTHIA	PHOJET
non-diffractive (ND)	48.5	61.6
single-diffractive (SD)	13.7	10.7
double-diffractive (DD)	9.3	3.9
Total:	71.5	76.2

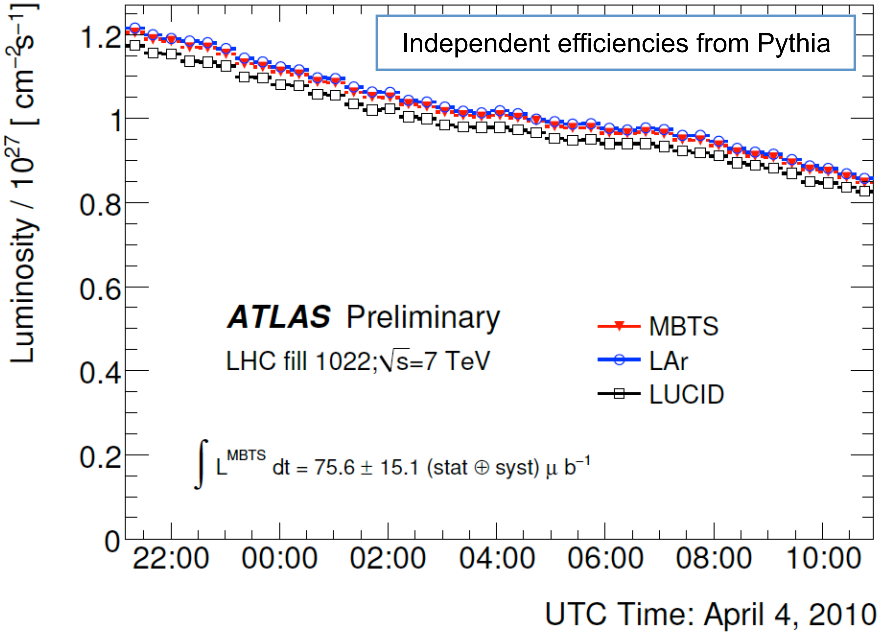
  - $\sigma_{ND/SD/DD}$ depend on physics model



	LUCID_Event_OR		LUCID_Event_AND		Primary Vertex Counting	
	7 TeV		7 TeV		7 TeV	
Process	Efficiency (%)		Efficiency (%)		Efficiency (%)	
	PYTHIA MC09	PHOJET	PYTHIA MC09	PHOJET	PYTHIA MC09	PHOJET
ND	79.2	74.2	30.8	25.5	97.8	99.2
SD	28.7	44.8	1.2	2.4	43.9	56.9
DD	39.4	62.0	4.4	14.8	47.8	70.7
σ_{vis} (mb)	46.1	52.9	15.5	16.4	57.9	70.0

- Modeling of detector response

Monte-Carlo-normalized $\mathcal{L}$: systematics



Internal consistency among MC -"calibrated" CMS luminosities

	$<\mathcal{L}>$	Online	HF Offline		Vtx Offline	
Fill	$(cm^{-2}s^{-1})$	L (μb^{-1})	L (μb^{-1})	Ratio	L (μb^{-1})	Ratio
1058	6.1×10^{27}	71.1	71.3 ± 1.2	1.004	74.4 ± 1.2	1.047
1089	2.0×10^{28}	230	234 ± 2	1.016	240 ± 2	1.041
1104	6.9×10^{28}	461	473 ± 4	1.026	485 ± 4	1.052

online pegged to offline HF

independent MC calibrations

Systematic uncertainties on MC -"calibrated" ATLAS $\mathcal{L}$ (7 TeV)

Source	Liquid Argon (%)	MBTS_1_timing (%)	LUCID (AND or OR) (%)	Charged Particle (%)
σ_{vis}	20	20	20	20
Detector response	5.5	n.a	5.0	2
Background	negligible	negligible	negligible	negligible
Trigger Efficiency	2	5	n.a	2
Total	21	21	20	20

The total systematic uncertainty is 100% correlated across methods.

- **Absolute Monte-Carlo "calibration" of luminosity**
  - **detector-modelling systematics at the ~ 4-5% level**
  - **+- 20% uncertainty from phyiscs**
    - **unknown mix of non-, single- & double-diffractive contributions**
    - **≠ acceptances for ND/SD/DD - and also ≠ for Pythia vs. Phojet**
    - **unknown total cross-section**

Luminosity as function of beam parameters

- The luminosity can be written in terms of the transverse spatial profiles of the interacting beams:

$$\mathscr{L} = n_b f_r I_1 I_2 \int \rho_1(x,y)\rho_2(x,y)dxdy$$

No crossing angle considered here

Number of bunches per turn

LHC revolution frequency

Number of protons/bunch in beams 1 & 2 (measured by LHC)

Overlap integral of the two normalized two-dimensional transverse beam profiles

- In the hypothesis of beam profiles uncorrelated in x and y:

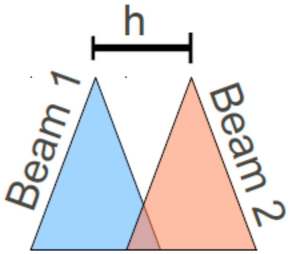
$$\mathscr{L} = n_b \cdot f_r \cdot N_1 \cdot N_2 \cdot I_x(\rho_1(x) \cdot \rho_2(x)) \cdot I_y(\rho_1(y) \cdot \rho_2(y))$$

- where one needs to measure the overlap integrals in x and y:

$$I_x(\rho_1(x) \cdot \rho_2(x)) = \int \rho_1(x) \cdot \rho_2(x) dx$$

Van der Meer scan formalism

- Idea:
  - Shift the beams with respect to each other in the horizontal or vertical direction (separation h)
  - Measure the rates as a function of h



$$R(h) = \mathrm{A} \cdot I_x(\rho_1(x) \cdot \rho_2(x-h))$$

- The overlap integral can be thus estimated as:

$$I_x(\rho_1(x) \cdot \rho_2(x)) = \frac{R(0)}{\int R(h)dh}$$

- Independent of the beam shapes!

$$\mathscr{L} = n_b \cdot f_r \cdot \frac{N_1 \cdot N_2}{2\pi \cdot \tilde{\Sigma}_x \cdot \tilde{\Sigma}_y}$$

Define “equivalent” Gaussian sigmas.

Double Gaussian appears to describe exp. data well:

Fraction of core Gaussian

Core sigma

Tail sigma

$$I_x(\rho_1(x) \cdot \rho_2(x)) = \frac{1}{\sqrt{2\pi}} \left[\frac{f_a}{\sigma_a} + \frac{1 - f_a}{\sigma_b} \right]$$

Fitting Formalism

- Parameterize the luminosity at the peak as

  $$\mathcal{L} = f_r\, n_b\, N_1\, N_2 \,/\, 2p\, S_x\, S_y$$

  where S_x, S_y provide a measure of the integral under the luminosity-scan curve (van der Meer's idea)

- If beams 1 & 2 are both Gaussian at the IP, then the $\mathcal{L}$-scan curves are also Gaussians of width

  $$\square_x = (s^2_{1x} + s^2_{2x})^{1/2} \quad \text{(and similarly for y)}$$

- If the $\mathcal{L}$-scan curves can be parameterized as double Gaussians of amplitudes $A_{n(w)}$, widths $s_{n(w)}$ and fractional integrals $f_{n(w)}$, then

  $$\square_x = (A_{nx}\, s_{nx} + A_{wx}\, s_{wx}) \,/\, (A_{nx} + A_{wx})$$
  $$= [f_{nx} / s_{nx} + f_{wx} / s_{wx}]^{-1}$$

  $f_i = A_i\, s_i / (A_n s_n + A_w\, s_w)$ is the fractional contribution of Gaussian *i* to the integral

- More generally, S = integral under the $\mathcal{L}$-scan curve / peak value R_{max}

Systematic uncertainties: bunch currents I_1, I_2

- 2 independent beam-current measurements
  - FBCT: bunch-by-bunch measurement (colliding vs. non-colliding bunches !)
    - integrates charge in 25 ns bins
    - highly sensitive to precise timing adjustment (phase wrt beam)
    - signal (not protons!) has been observed to leak in neighbouring bin
  - DCCT: total beam-current measurement (including debunched p, if any)
    - designed to provide 1% accuracy … with 10^{14} circulating protons !
    - noisy at low current (not an issue: scan step ~ 10-30 secs)
    - requires baseline compensation ($5\ 10^8$ - $5\ 10^9$ p), with poorly known time variation, temperature sensitivity

- Corrections to original (= raw) bunch current data by expert
  - reassign leaked charge to proper BCID (time bin)
  - rescaled sum of BCT bunch currents (1 colliding + 1 non-colliding) to DCCT measurement
  - Total change of ($I_1 \times I_2$): 13% for scan I, 9% for scan II